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**Geologic mapping and sedimentologic analysis of Quaternary deposits
along the western shore of Flathead Lake, northwest Montana;
documenting the record of deglaciation**

by

Amy K. Bondurant

B. S. College of Charleston

Presented in partial fulfillment of the requirements

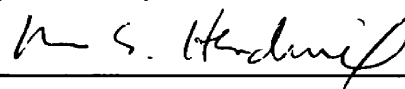
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Master of Science

The University of Montana

December 2005

Approved by:



Chairperson



Dean, Graduate School

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Geologic mapping and sedimentologic analysis of Quaternary deposits along the western shore of Flathead Lake, northwest Montana; documenting the record of deglaciation

Chairperson: Marc Hendrix *MSH*

During the last glacial maximum, a major lobe of ice flowed southward down the Flathead Valley of northwest Montana and terminated near the present day site of Flathead Lake. The sediments left behind by this glacial system provide a detailed record of ice advance and retreat associated with the Cordilleran Ice Sheet. The overall focus of this study has been to describe the sedimentology and geomorphology of features associated with this former ice margin. The study area is located in the Big Arm Embayment (Elmo, Proctor/Dayton, and Big Arm Valleys) on the westside of Flathead Lake. These valleys share similar geomorphic features, including terminal and lateral moraines, proglacial lake sediments, and outwash plains. These landforms define the western ice limit of the Flathead Lobe and are helpful for determining the spatial and temporal relationships between Glacial Lake Missoula and the ice sheet. Documenting the relative age relationships of ice margin deposits is an important issue because the lack of radiometrically dateable material has resulted in very poor absolute age control for Quaternary deposits of the Flathead Valley. Through detailed mapping of glacial sediments and their associated geomorphic landforms, I was able to determine the relative timing of glacial and deglacial events associated with the former ice marginal system. For example, measurements of paleocurrent indicator directions in each of the three valleys delineate outwash drainage directions and suggest the presence of a spill point in the Elmo Valley. Initial draining of proglacial Lake Flathead during deglaciation of the Flathead Lobe began at the Elmo spill point and proceeded until the lake level fell below the spill point elevation and flow was cut off. The southern outlet of proglacial lake Flathead near the Polson moraine then continued to drain the lake until a stable lake level was established.

Sedimentologic analyses of the Quaternary deposits aided in determining the aquifer potential of the sediments. Glacial lake and morainal sediments are poor aquifers due to low porosity and silty lithologies. The most productive aquifers consist of the outwash (Gm, Sr/Sh) and lake terrace (Sm) facies due to the presence of massive sands and gravels.

Acknowledgements

I would like to thank Dr. Marc Hendrix for his guidance, patience, and support throughout my graduate program. I would also like to thank Dr. Joel Harper and Dr. Eric Edlund for their guidance and influence as my committee members. I also thank Michael Hofmann for his constant support and brilliant knowledge of everything that is Glacial Lake Missoula, without his influence I would never have chosen the field of glacial geomorphology. I would like to acknowledge the whole geology department for their support in moving me across the country and for the knowledge that I have gained here. I would also like to thank the community of Big Arm Bay, specifically, the Grende's, Thompson's, and the Meuli's for permitting me access to their land, feeding me, and discussing my theories. I also thank the Confederated Salish and Kootenai tribes for providing land access. This research would not have been conducted without financial support provided by USGS-EDMAP grant # 04HQAG0102.

I would like to thank my family for their constant love and support for me and for my dreams. I would also like to thank my mapping partners Garrett and Ed for the campfires in the cow field, the rope swings, and of course the many entertaining car rides in Patches. Thank you to everyone who helped me in the field, especially Donovan Power, Sheetal Patel (for almost blowing up the place), Robyn Cook, Michael Hofmann (again you are my mentor), and Vixen. Caruthers, physics would not have been the same without you. To Ryan, thank you for the magic you have brought to my life and for the wonders we have yet to experience. To all of my geo buddies thank you for making my time here in Missoula so fabulous.

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Plate I. Geologic map of the Big Arm Embayment

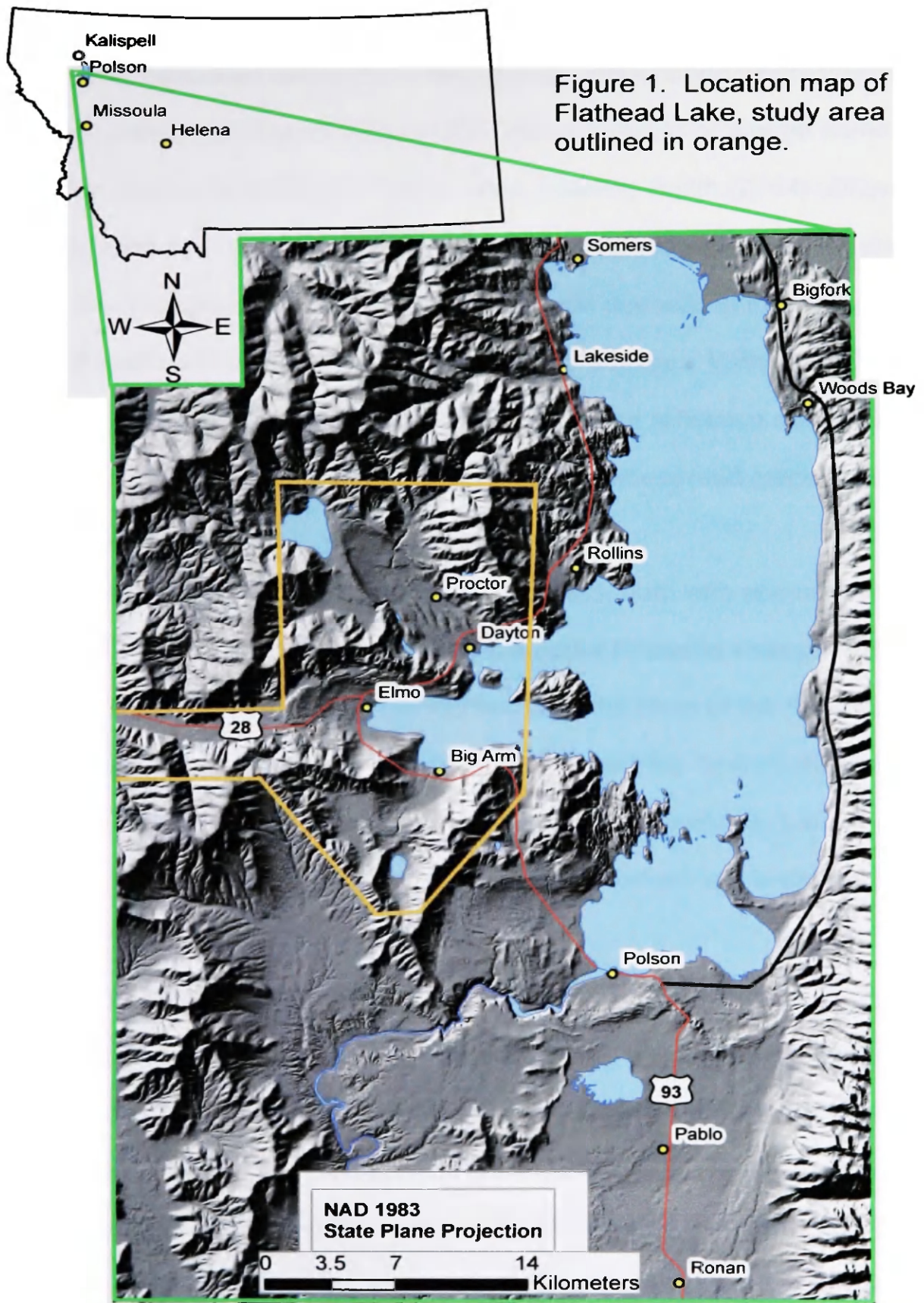
Plate II. Cross-Sections of the Big Arm Embayment

Introduction

During the last glacial maximum, a major lobe of ice flowed southward down the Flathead Valley of western Montana and terminated near the present day site of Flathead Lake. The sediments left behind by this glacial system provide a detailed record of ice advance and retreat associated with the Cordilleran Ice Sheet.

The primary focus of this study is to describe the sedimentology and geomorphology of features associated with this former ice margin. Herein, I present results from standard onshore geologic mapping along the western side of Flathead Lake in order to document the distribution of glacial and post-glacial deposits associated with the former ice margin. I describe the sedimentology of these deposits in order to develop a more clear understanding of the paleogeography and hydrostratigraphy associated with glacial and post-glacial conditions, and I present a series of cross-sections depicting the subsurface geology of each of the three main valleys in the study area, based on well-log lithologic data and correlation with surficial facies units.

Numerous studies have concluded that the Flathead lobe of the Cordilleran ice sheet extended into the Flathead Lake region of western Montana during the late Pleistocene (Elrod, 1903, Pardee, 1942, Nobles, 1952, Alden, 1953, Smith, 1966). For example, in the Big Arm and Elmo Valleys, located immediately west of Flathead Lake (Fig.1), Smith (1966) recognized two sets of Quaternary lateral and terminal moraines with associated proglacial deposits.



In the Proctor Valley, located just west of Flathead Lake (Fig.1), Smith (1966) also described remnants of two glacially influenced Gilbert-style deltaic systems; Johns (1964) and Beaty (1962) cited evidence of a large kame terrace along the north side of Proctor Valley. More recently Smith (2004) utilized geologic mapping, detailed sedimentologic studies and water well-log data to define the stratigraphy of glacial and post-glacial deposits in the Flathead Valley north of Flathead Lake and to infer subglacial processes. Within the Flathead Lake basin itself, Hofmann and Hendrix (2004) used reflection seismic imaging and piston core analysis to infer the presence of widespread glaciolacustrine sedimentation.

Hydrogeologically, two productive aquifers, both with above average porosity values, have been identified in the upper Flathead Valley (Smith, 2000b). The lower aquifer layer is located near the base of the Pleistocene strata a few meters above the boundary with underlying Tertiary deposits and consists mainly of stratified sands and boulder conglomerates (Lafave and Smith, 2004). The upper aquifer is located in shallow alluvium and shoreline sands and gravels from ancestral lake Flathead.

Despite general agreement that the Flathead Valley was recently glaciated, surprisingly little is known about the specific distribution of glacial and glaciolacustrine deposits in the vicinity of the former ice margin (Nobles, 1952; Alden, 1953; Smith, 1966; Smith, 2004). Understanding the distribution of these deposits and their sedimentology is important because they represent the most complete and best preserved record of glacial dynamics near the former terminus

of the Flathead Lobe. Understanding the subsurface geology and the distribution of porous, permeable lithofacies is important because increased development on the west side of the lake has placed a larger demand on groundwater supplies in the area.

The physical and temporal relationships between Glacial Lake Missoula and proglacial depositional systems associated with the Flathead Lobe are key to understanding the Quaternary history of this field location. Documenting the relative age relations of ice margin deposits is important because the lack of radiometrically dateable material has resulted in very poor absolute age control for Quaternary deposits of the Flathead Valley. Through detailed mapping of glacial sediments and their associated geomorphic landforms, I was able to determine a relative ordering of glacial and deglacial events associated with the former ice marginal system. By building upon and integrating results from previous studies (Elrod, 1903; Meizner, 1917; Shenen and Taylor, 1936; Smith, 1966; Sears, 1991), I developed a regional paleogeographic picture for establishment and retreat of the Flathead Lobe terminus in the study area and its relationship to glacial Lake Missoula. For example, my mapping results allowed me to recognize varved, glaciolacustrine sequences that are observed in offshore cores from Flathead Lake (Hofmann et al., 2003). These varved sequences are important because they provide the basis for estimating sedimentation rates and ice sheet positions as well as providing new information regarding the depositional setting of individual parts of the ice marginal system.

Regional geology and physiography of the area:

The study area is located within the Big Arm Embayment which encompasses the Big Arm, Elmo and Proctor Valleys and is located along the west side of Flathead Lake, northwestern Montana (Fig. 1). Flathead Lake reaches its maximum depth of > 100m in its eastern part. In contrast, Big Arm Bay is relatively shallow at 10-35m. The Flathead drainage basin has an area of ~18,000km² and encompasses the North Fork, South Fork, and Middle Fork of the Flathead River basins and drainages associated with the Swan, Stillwater, and Whitefish Rivers (Joyce, 1980). Flathead Lake has only one outlet on its southern margin through which the lower Flathead River drains.

The Flathead Lake basin itself (Fig. 2) lies in a north-south trending extensional half-graben bounded on the east by the Mission fault, a normal fault. The Whitefish Range and Swan Mountains border the Lake to the northeast while the Salish Mountains (part of the Flathead Range) and Hog Heaven Volcanic complex border the lake to the west (Fig. 2). The Flathead Valley is interpreted to be the southern extension of the Rocky Mountain Trench, a laterally continuous group of valleys that extends northwest from the Lewis and Clark Zone for about 1500 km into Canada (Osteena et al., 1990, Fig. 2).

Structurally, the Big Arm Embayment is located within the eastern limb of the Purcell Anticlinorium, a NNW-trending structural feature of western Montana (Harrison et. al., 1986; Sears, 1991).

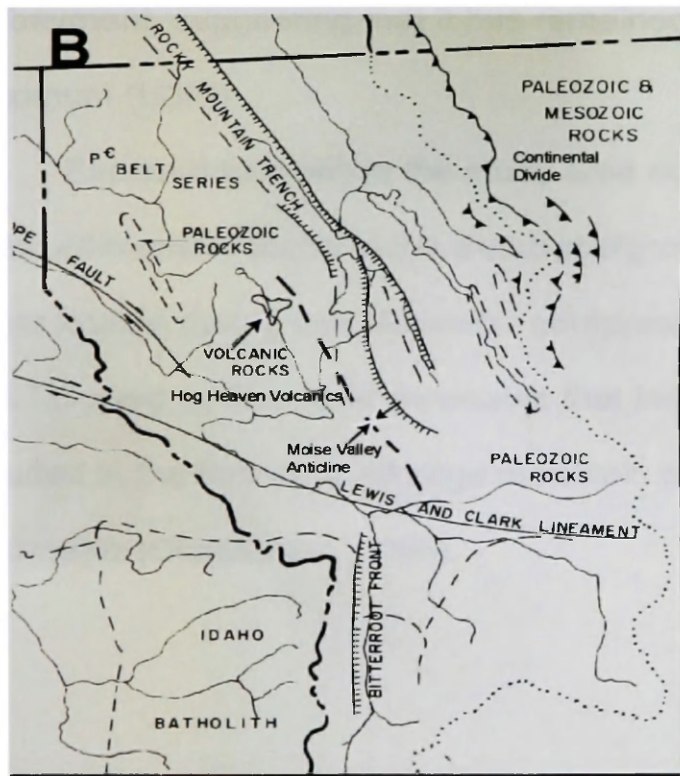
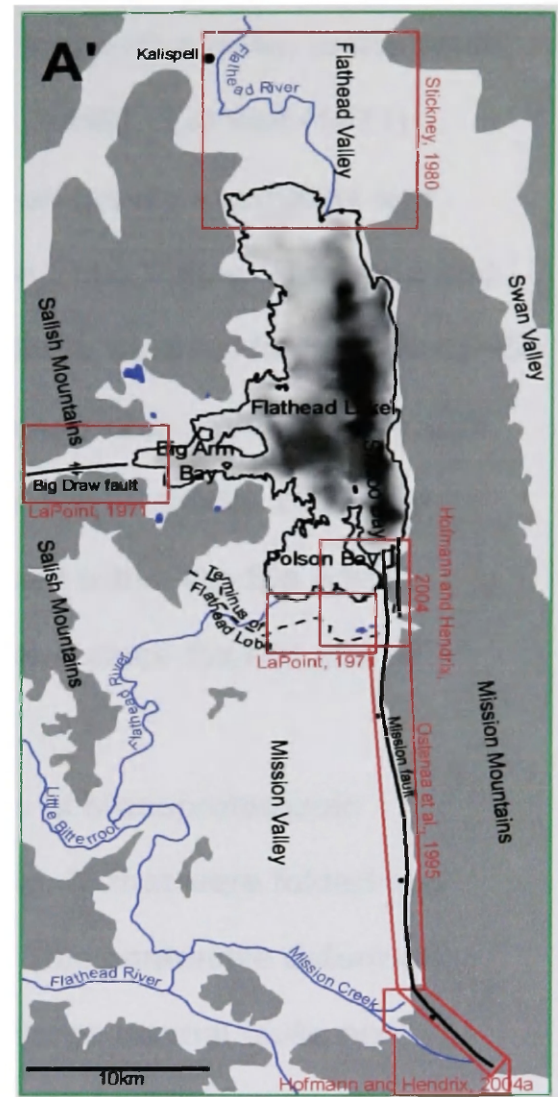
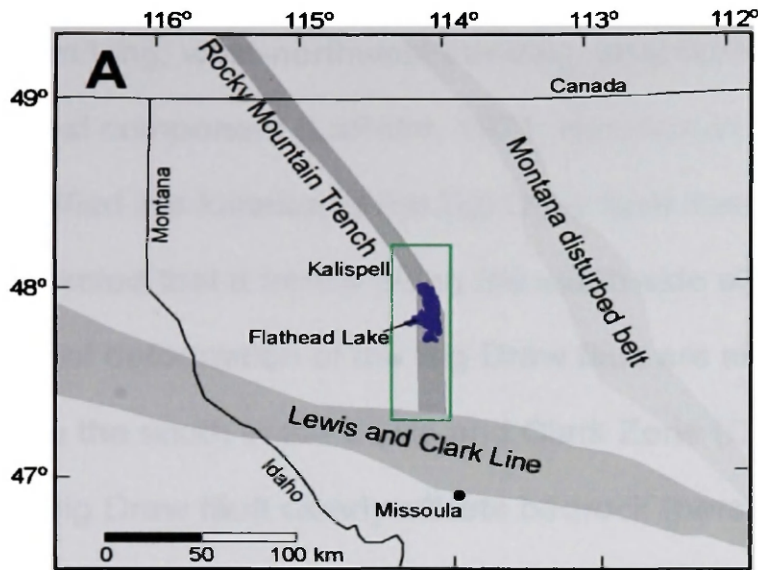


Figure 2. (A) Tectonic map of northwestern Montana. (A') A close-up of Flathead Lake listing previous structural studies (Modified from Hofmann et al., in press). Southern margin of Polson moraine (terminus of FHL) represented by dashed line. (B) Geologic map of northwest Montana focusing on the large structures and igneous intrusions (Modified from LaPoint, 1971).

The dominant structure within the Big Arm Embayment is the Big Draw fault, an 84-km long, west-northwest trending, right-lateral fault with a down to the south normal component (LaPoint, 1971; Harrison et al., 1986). LaPoint (1971) identified the location of the Big Draw fault based on gravity anomalies and suggested that it trends along the south side of the Elmo Valley. The trend and style of deformation of the Big Draw fault are similar to those of faults located ~50 km to the south in the Lewis and Clark Zone (Osteena et al., 1990). Although the Big Draw fault clearly offsets bedrock (pers. comm., Salmon, 2005), no geomorphic evidence of the fault has been observed within the Big Arm Embayment, suggesting that it has remained inactive since the last glacial maximum (LGM).

Exposed bedrock in the study area consists of Mesoproterozoic metasedimentary rocks of the Belt Supergroup (Fig. 3) that were folded and thrust faulted during late Mesozoic compression. This contractile deformation was followed by Cenozoic extension that initiated large normal faults and resulted in the formation of large mountain ranges such as the Mission Mountains (Constenius, 1996).

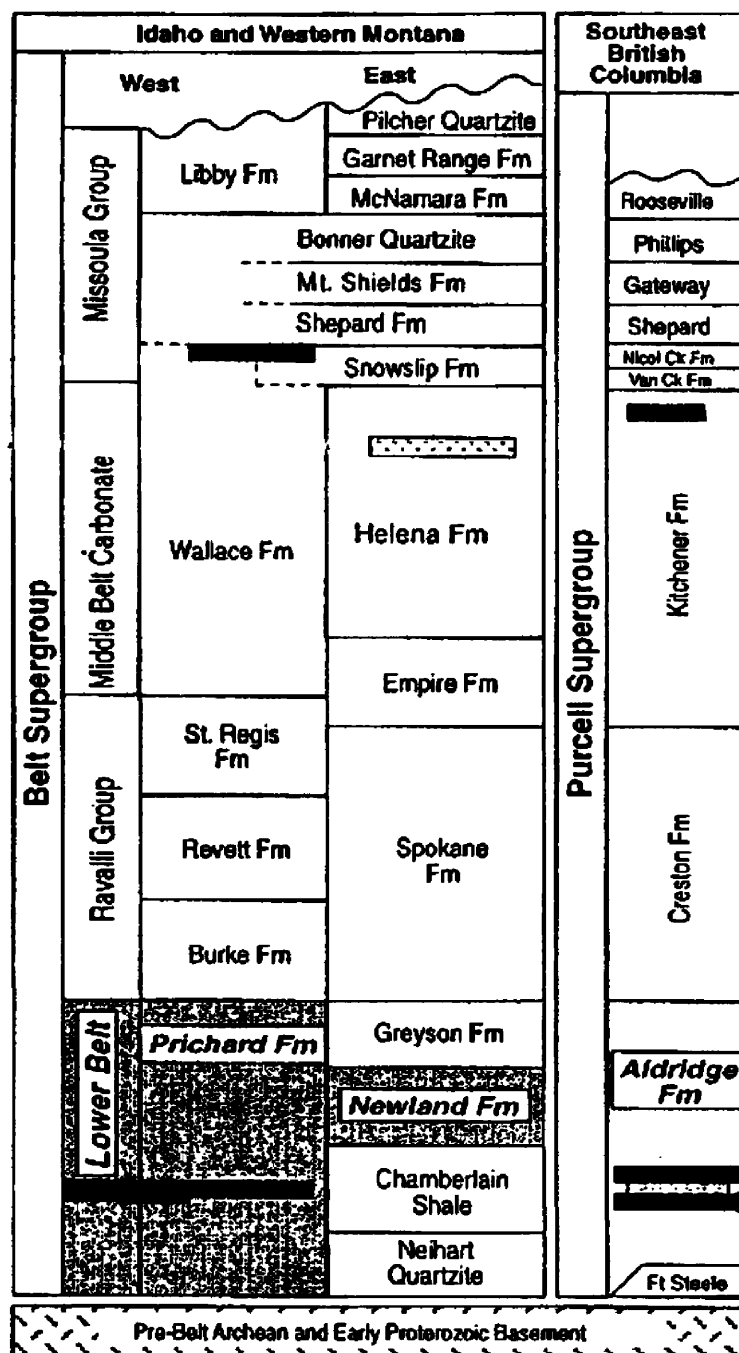


Figure 3. Stratigraphy of the Belt Supergroup (after Luepke and Lyons, 2001).

In the study area, bedrock is dominated by the Ravalli group and the Empire and Helena Formations (Fig. 3). The Ravalli group consists of thin to medium bedded, gray to reddish argillites and quartzites whereas the Empire and Helena Formations are composed of calcareous gray, green, and purple argillite, limestone and dolomite (Decker, 1968). Gravity surveys completed by La Point (1971) and borehole descriptions by Smith (2000a) alluded to the deposition of as much as 1500m of Tertiary and Quaternary sediments overlying bedrock in the valley.

The Hog Heaven volcanics are Tertiary in age and are composed mainly of latite tuffs (Lister, 1981). The majority of associated Tertiary-aged sediments are described as rounded cobbles and pebbles commonly found in the Kishenehn Formation and Paola gravel (Constenius, 1996). No Tertiary gravels were found in the study area, probably because of removal by glacial erosion and/or subsequent covering by glacial deposits. Quaternary sediments are of glacial origin within the study area and consist mainly of moraine or outwash plain deposits. Some low-lying areas are inundated with glacial lake sediments (Fig. 4).

During the Wisconsin stage of the Pleistocene, the Flathead Lobe (FHL) of the Cordilleran Ice Sheet inundated the Flathead Valley (Fig 5). Glacial ice contributions to the FHL were provided by ice flowing out of the Whitefish and Swan Ranges (Witkind, 1978a).

Period	Epoch	Name	Description	Interpretation
Quaternary	Holocene	deglacial and postglacial deposits	Sand and gravel with minor silt and clay within major river valleys and in broad sheets.	Outwash, eolian sand sheets and dunes, fluvial, alluvial, and alluvial fan deposits.
		ancestral Flathead Lake deposits	Brown and gray, laminated, calcareous fine sandy silt, clayey silt, and minor clay; cross-stratified and wave-rippled sand, sandy silt, and gravelly sand exposed near recessional moraines; generally not permeable to groundwater except for beds of sand and gravel; deposit has mostly flat upper surfaces.	Most deposited from suspension in lake that was initially pro-glacial; few gravels deposited from melting ice; subaqueous outwash fan deposits near recessional moraines; higher lacustrine deposits were abandoned successively as the lake receded.
	transitional			
	Pleistocene	laminated silt and clay deposits		
		diamicton	Massive diamiction: Gravel and boulders in a matrix of gray and brown dense sand, silt, and clay; generally not permeable to groundwater; clasts typically rounded and subrounded metacarbonate, quartzite, argillite, and diorite; more resistant clasts commonly striated; associated landforms include drumlins, terminal moraines, hummocky moraine, and eskers Bedded diamiction: 0.3->2 m diamictions locally interbedded with 0.05-0.2-m-thick beds of sorted sand and sandy gravel. Intermediate alluvium: stratified sand and gravel; single or multiple beds in any given area; permeable to groundwater.	Massive diamiction: mostly till deposited subglacially by lodgement and melt-out processes; surface is marked by englacial or subglacial eskers, supraglacial ablation deposits, drumlins, and moraines; Bedded diamiction: flow till and debris flow deposits; typically reworked in ice-contact environments. Intermediate alluvium: englacial or subglacial alluvial deposits that are encased in till.
intermediate alluvium				
deep alluvium	Brown, yellowish brown, and gray stratified coarse-grained sand and gravel conglomerate; rare calcium carbonate cement; clasts of quartzite, argillite, and metacarbonate.	Outwash deposited during glacial advance; may include some intraglacial alluvium.		
unconformity				
Tertiary	Eocene-Miocene(?)	Tertiary sediment and sedimentary rocks	Brown and orange medium- and coarse-grained pebbly sandstone; pebble and cobble conglomerate; carbonaceous shale and carbonized wood; gray, yellow, and orange mudstone; and orange clayey gravel (diamiction); gravel clasts of argillite, quartzite, and siltstone are mostly well rounded; sandstone and conglomerate beds have channelized, erosional bases; locally infills fractures in Belt Supergroup bedrock; may include strata of the Kishenehn Formation and Paola gravel (Constenius, 1996).	
unconformity				
Proterozoic		Belt Supergroup	Numerous stratigraphic units composed mostly of metamorphosed siltstones, carbonates, and quartz sandstones and minor amount of igneous rocks; most bedding thicknesses range between less than 1 cm in metasiltstones to a few decimeters or a few meters in metacarbonates and quartzites (Johns, 1970).	

Figure 4. Stratigraphy of Flathead Valley (from Smith, 2004).

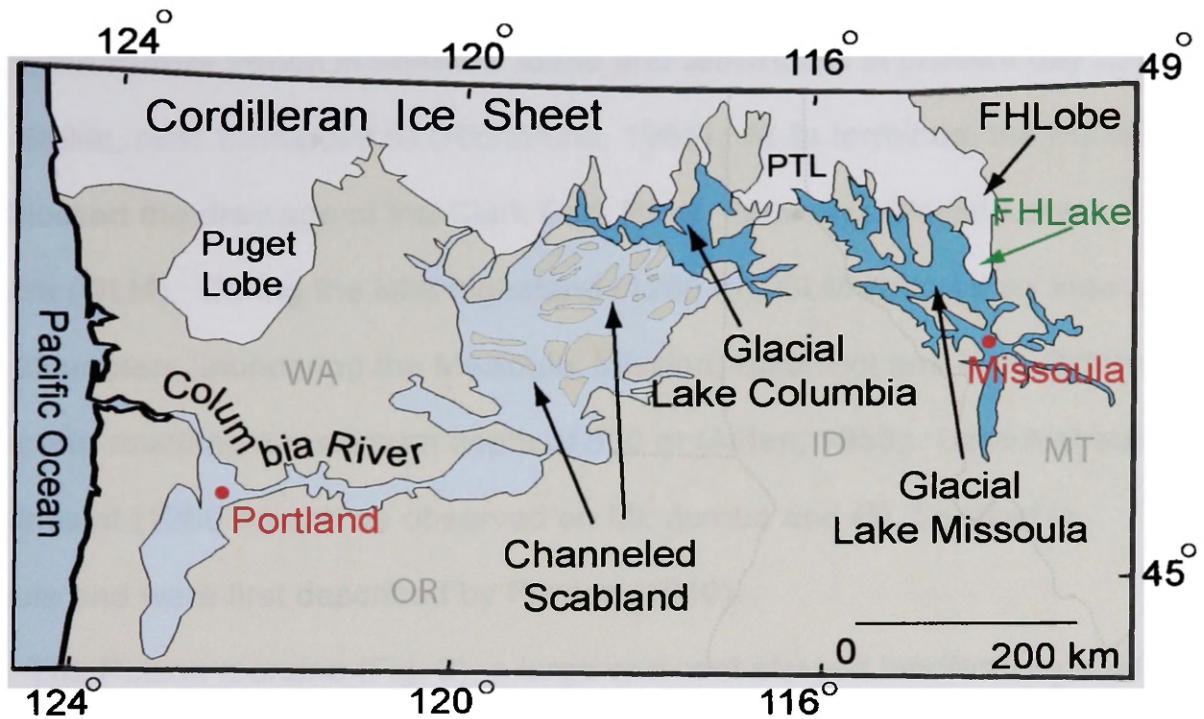


Figure 5. Schematic map showing the southern margin of the Cordilleran Ice Sheet, glacial Lake Missoula, glacial Lake Columbia and the Channeled Scabland. PTL = Purcell Trench glacial lobe. The PTL formed glacial Lake Missoula by blocking the Clark Fork River. FH Lobe = Flathead glacial lobe; FH Lake = present location of Flathead Lake; Map modified from Waitt, 1985.

At the border of Canada and the US the maximum thickness of the Flathead Lobe reached ~1500 m, but rapid thinning of the ice sheet to the south resulted in a thickness of ~800 m in Kalispell, MT (Alden, 1953). Coinciding with the inundation of the Flathead Valley by the FHL, the Purcell lobe (Fig.5) flowed through the Purcell trench in northern Idaho and terminated in present day Lake Pend Oreille, near Sandpoint ID (Richmond, 1965). At its terminus, the Purcell Lobe blocked the drainage of the Clark Fork River, damming Glacial Lake Missoula (GLM). During the lake highstand (1280 m), GLM covered an area of 5,000 kilometers, inundating the Missoula, Mission, Bitterroot and Little Bitterroot valleys and reaching a maximum depth of 600 m (Alden, 1953). Lake highstand shorelines at (1280 m) can be observed on Mt. Jumbo and Mt. Sentinel in Missoula and were first described by Pardee (1910).

The Polson moraine (Fig. 2), a large crescent-shaped landform located at the southern end of Flathead Lake marks the southern terminus of the FHL during the time of LGM and displays wavecut shorelines on its southern slope. The hills in and around the Flathead Valley display prominent shorelines at 975 m and 950-955 m, possibly signifying a period of lake-level stability when the Flathead Lobe terminated in GLM, at least for a portion of its history (Richmond et al., 1965,1986; Stoffel, 1980; Levish, 1997; Smith, 2004). Multiple drainings of GLM have been inferred based on studies by Chambers (1971) and Atwater (1986), although correlations between flood sediment outside the lake basin and within the lake basin are controversial (Smith, 2004). GLM sediments are

defined in the current study as varved and consisting of silt/clay rhythmite sequences with local dropstones.

Glacial Setting

The three valleys adjoining the Big Arm Bay (from south to north, Big Arm, Elmo, and Proctor/Dayton Valley) all share similar geomorphic features, including terminal and lateral moraines, proglacial lake sediments, and outwash plains. These features indicate proximity to the ice margin during the last glaciation (Fig 6). All three valleys slope towards present day Flathead Lake and are separated by east-west trending bedrock ridges that rise about 300- 450 m above the valley floors (Smith, 1966).

Proctor Valley is the largest of the three valleys and contains well preserved Gilbert-style deltas, terminal and lateral moraines, and proglacial lake sediments. Lake Mary Ronan, located at the NW edge of the Proctor valley that was dammed by the deposition of the Proctor moraine ("Dayton Valley moraine" of Smith, 1966) drained through a southern outlet into Big Meadows (Fig. 6) that now contains the meandering Ronan Creek. A large deltaic feature is located in the Proctor Valley near the headwaters of Dayton Creek (Fig. 6).

The dominant morphologic feature of the Elmo valley is the Elmo moraine. It forms a rough hummocky terrain and is the present drainage divide between the Little Bitterroot drainage and Flathead Basin (Smith, 1966). Pro-glacial lake sediments of an older, glacial lake Flathead are found within the drainages of the Elmo Valley and in the town of Elmo.

Legend

terminal moraines

field area

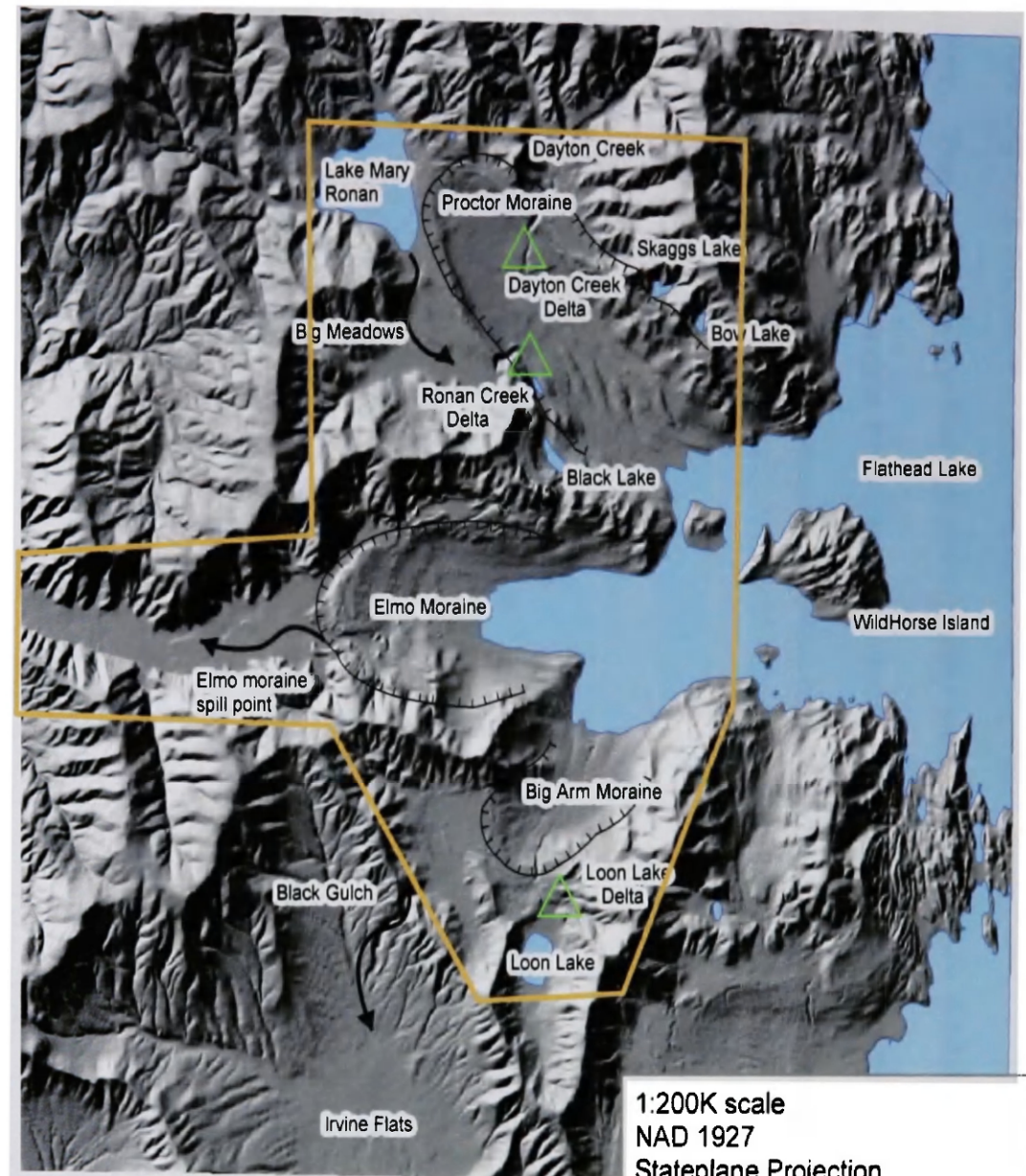
outwash
flow direction

Delta



0 2 4 6 8 Kilometers

14



1:200K scale
NAD 1927
Stateplane Projection
data source: NRIS MT state library

Figure 6. Location of major geomorphic landforms in the Big Arm Bay, MT.

The Big Arm moraine is located about three miles southwest of the town of Big Arm. The drainage for the Big Arm glacier was Black Gulch, a bedrock nick point that drained into Irvine Flats (Fig 6). Loon Lake, a present day ephemeral lake, appears to have occupied a pro-glacial lake setting during most of the Pinedale glaciation.

Glacial Geochronology

During the Wisconsin stage of the Pleistocene, the Cordilleran ice sheet spread over the Northern Rocky Mountains of Montana and parts of Idaho and Washington (Fig. 5). Locally, the last glacial period (~25-14 ka ^{14}C y BP) is referred to as the Pinedale glaciation that is synonymous with the Fraser glaciation of British Columbia, Canada and northern Washington, USA (Fig. 7). One absolute date that constrains the Purcell Lobe and the FHL is the Glacier Peak tephra, 11,200 ^{14}C y BP (Carrara et al., 1986). Radiocarbon dates and pollen recovered from a bog on a moraine near the town of West Glacier indicate that the region had been deglaciated prior to the deposition of the ash and re-vegetation of the area (Carrara, 1989). The presence of Glacier Peak ash and Mount St. Helens Jy ash (11,400 ^{14}C y BP) at Marias Pass provide a relative timeline of deglaciation along the continental divide of Montana (Carrara, 1989). Elk River Basin, B.C., located ~30 km north of the USA-Canada border along the northern Rocky Mountain trench was filled with a tributary glacier of the Cordilleran Ice Sheet that flowed into the FHL.

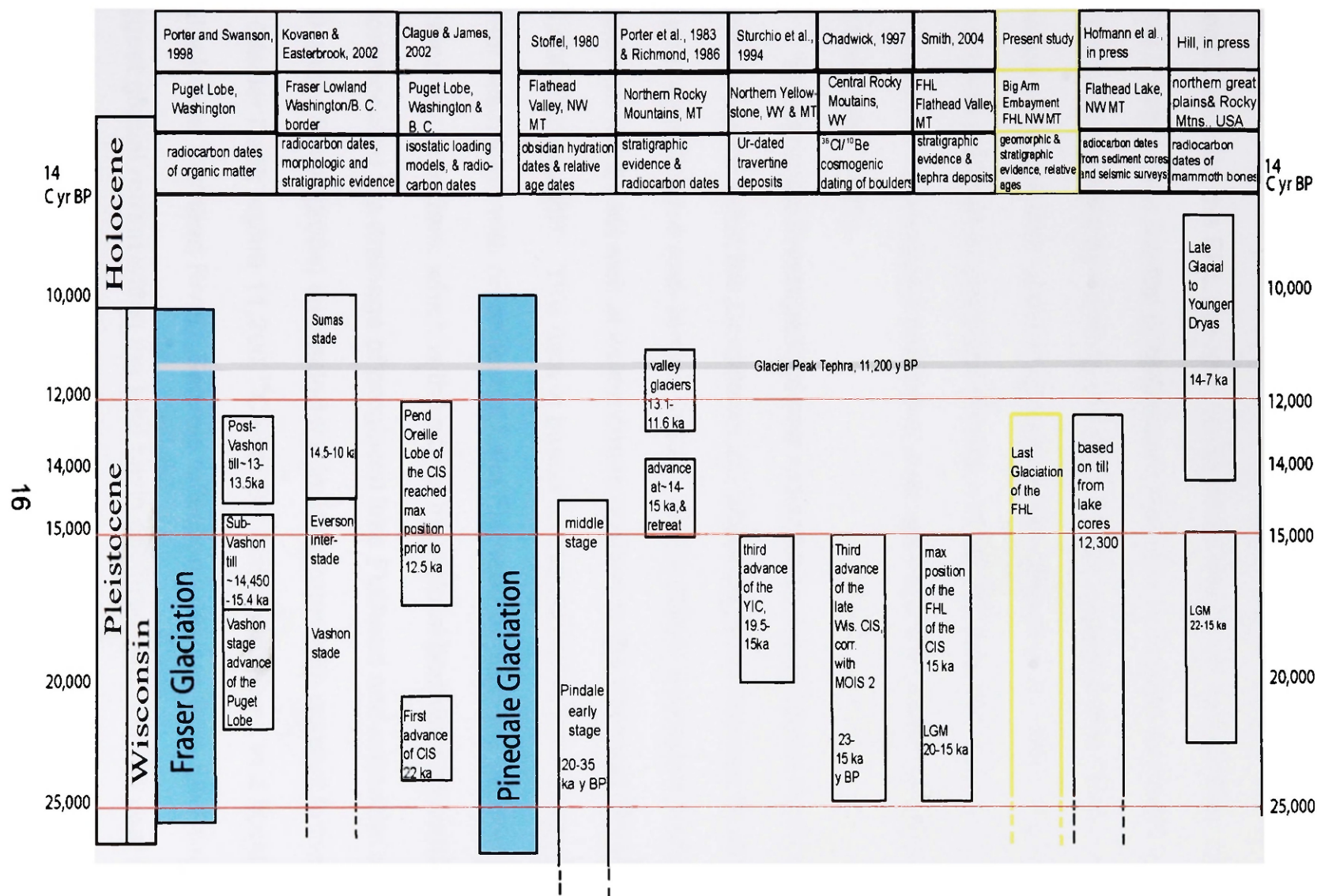


Figure 7. Glacial chronology table of the Cordilleran Ice Sheet during the Wisconsin. (CIS, Cordilleran ice sheet; FHL, Flathead Lobe; LGM, Last Glacial Maximum; YIC, Yellowstone ice cap; MOIS, Marine Isotope age).

Radiocarbon dates of shells found in a bog in the Elk River basin constrain the deglaciation of the Rocky Mountain trench as occurring between 13,500 and 12,000 ^{14}C year BP (Waite and Thorson, 1983; Carrara, 1989). The retreat of the Purcell Lobe and the FHL are also constrained based on radiocarbon dates of tephra located near the top of slackwater deposits perceived by Begét et al., (1997) to be sourced by draining of GLM. These deposits were found at an advance stage ice limit of the Puget Lobe, WA (Begét et al., 1997, Fig. 5). The Puget Lobe reached its southern limit by ~ 14 ka ^{14}C year BP (ca. 16,950 cal year ago) based on radiocarbon dates and average maximum advance rates (Porter and Swanson, 1998).

Stratigraphic investigations and radiocarbon dates across much of B.C., Canada suggests that the Cordilleran Ice Sheet began to develop 30,000-25,000 ^{14}C year ago (Clague and James, 2002). Smith (2004) estimated that the Cordilleran Ice Sheet was at its maximum position in the Flathead Valley by $\sim 15,000$ ^{14}C year BP. This date is based on incision rates from downcutting events associated with an ancestral Lake Flathead through the bedrock at present day Kerr Dam, which is the site of the natural bedrock nickpoint that accommodated the drainage of proglacial lake Flathead and ancestral lake Flathead. Smith (2004) calculated the incision rates with respect to the age of the Glacier Peak tephra 11,200 ^{14}C year BP that is preserved in a fluvial terrace on the Lower Flathead River. Seismic reflection analyses from Flathead Lake suggest glacial retreat within the lake basin occurred $\sim 13,000$ ^{14}C year BP. This interpretation is based on the presence of Glacier Peak tephra in a package of

rhythmite layers of silt in cores recovered from Flathead Lake. The rhythmite layers overlie glacial tills inferred to be related to the last major glacial advance of the Cordilleran Ice Sheet (Hofmann et al., in press). In this study, I infer that the glacial landforms in the study area formed from ~25,000 to 12,300 ^{14}C year BP during the last Pinedale glaciation of the FHL (Fig. 7). Although the study area was largely ice free by ~12,000 ^{14}C year BP, the Cordilleran Ice Sheet persisted until about 11,000-10,500 ^{14}C year BP mostly near the southwestern coast of B. C. and northern Washington (Clague and James, 2002).

Methods

I used standard geologic mapping techniques and sedimentologic analysis to define Quaternary stratigraphic units within the Big Arm Embayment. I used six USGS 1:24,000 topographic quadrangles as a base map; Irvine Lookout Tower, Elmo, Proctor, Lake Mary Ronan, Rollins, and Buffalo Bridge. A digital elevation map (DEM) of the field area (Fig. 6) aided in defining the geomorphic landforms. I obtained the baselayer DEM of the Big Arm Bay from the Montana NRIS (natural resource information system) website, which lists all available GIS data. All of the layers are projected in the same state plane coordinates with a NAD 1983 projection. ArcToolbox transformed the grid data into a raster format that is standard for ArcMap procedures. I overlaid the image with a hillshade in order to better define the topography (Fig. 6). I also used the DEM in conjunction with aerial photographs to define crosscutting relationships involving outwash

channels and terraces useful for determining relative ages. I used a Garmin Etrex Vista GPS unit to obtain elevation data and geographic locations (appendix 2). Cross-sections based upon well data acquired from the Montana Bureau of Mines and Geology (MBMG) and indexed to surficial deposits provided the basis for my interpretation of the subsurface geology of the study area. I used my outcrop observations and descriptions provided by Smith (2004) to interpret the lithologic content of the well logs. I measured stratigraphic sections in the two major active gravel pits located in Proctor and Elmo, along major road cuts through the Elmo moraine, and along active drainages in the Proctor/Dayton Valley (Fig. 8-11). I based analyses of clast compositions in pebble and cobble bearing units on individual clasts identification within a 1x1 square meter area. I conducted clast counts in each of the three valleys at various elevations in order to define provenance and ice sheet elevations, and I measured orientations of an average of fifty glacially striated lineations at scoured bedrock localities using a Brunton azimuth compass. I used RockWorks software to plot bedrock scour orientations on rose diagrams (map plate 1). I digitized my geologic map (map plate 1) using ArcGIS 8.3 software by manually drafting my geologic contacts using on screen digitizing techniques and standard topologic rules.

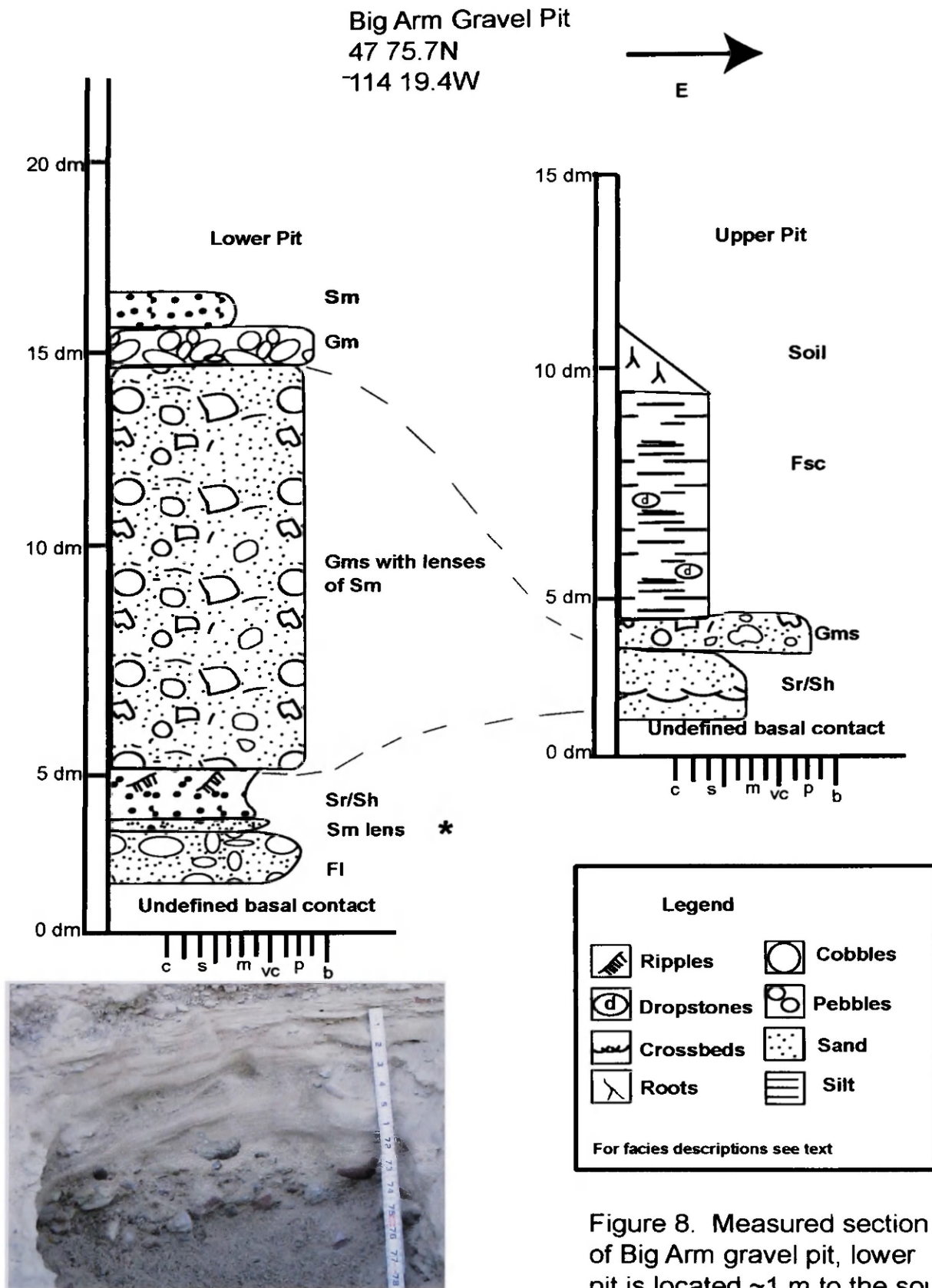


Figure 8. Measured section of Big Arm gravel pit, lower pit is located ~1 m to the south of the upper pit.

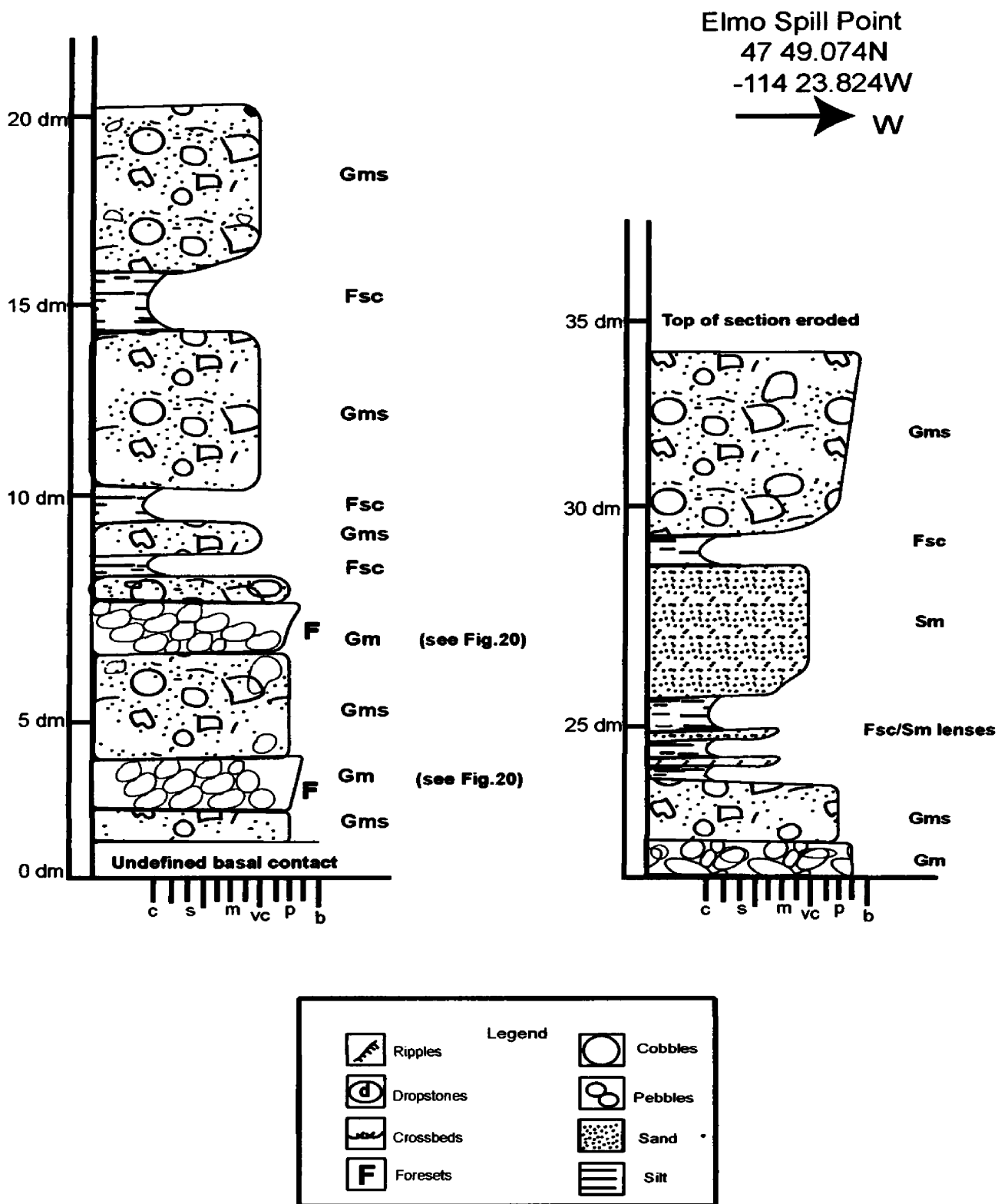
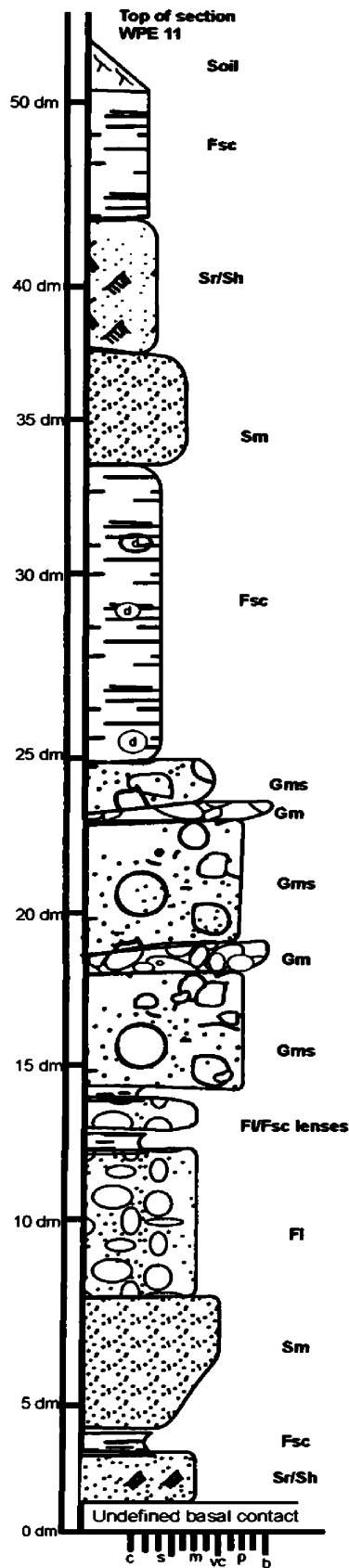


Figure 9. Measured section of the Elmo spill point, the sections were staggered due to erosion of the outcrop.



Elmo Valley Moraine
Composite Section
WP E10
47 49.218 N
-114 23.51 W

← W

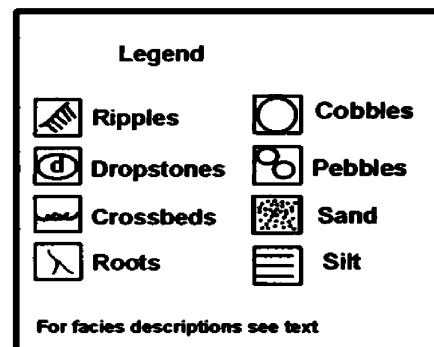


Figure 10. Measured section of Elmo Valley moraine.

Ronan Creek Drainage
WP ROC1

← E

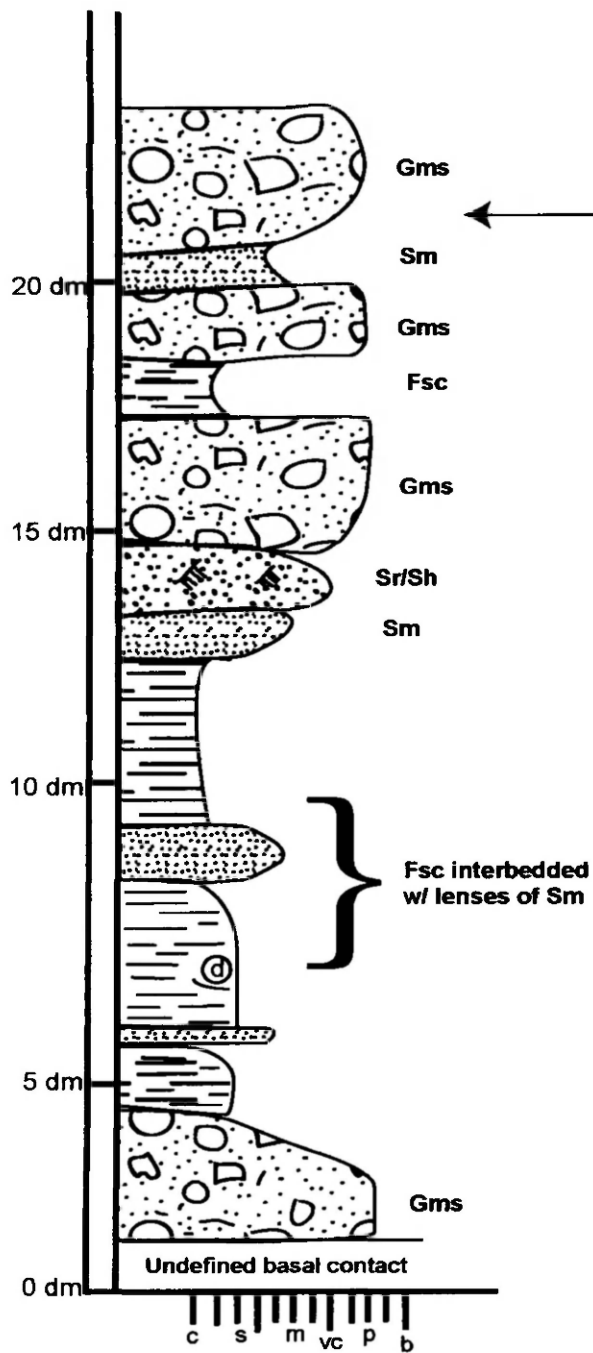


Photo of soft-sediment deformation (scale is cm).

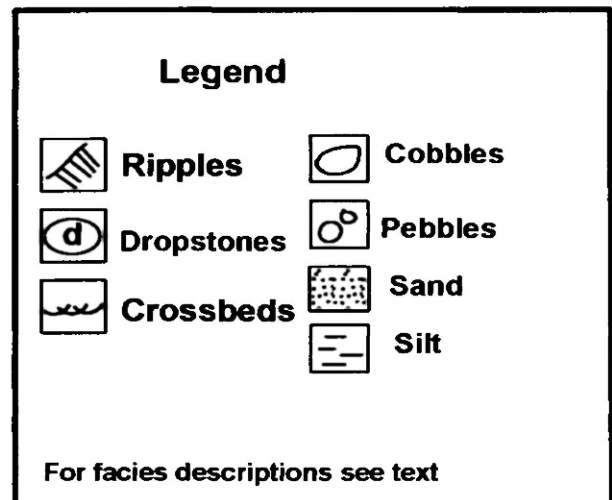


Figure 11. Measured section along Ronan Creek, Proctor Valley.

Results

Lithofacies

To define observed facies within the study area, I utilized a descriptive (allostratigraphic) terminology based upon studies by Brookfield and Martini (1999). I defined the following geologic units based upon my interpretation of geomorphic landforms and their sedimentology, using lithofacies codes of Miall (1978) and Eyles (1983) (Fig. 12).

TABLE 7.1 Facies Codes for Fluvial and Related Sedimentary Facies

Facies Code	Lithofacies	Sedimentary Structures
Gms	Massive, matrix-supported gravel	None
Gm	Massive or crudely bedded gravel	Horizontal bedding, imbrication
Gt	Gravel, stratified	Trough cross-beds
Gp	Gravel, stratified	Planar cross-beds
St	Sand, medium to very coarse; may be pebbly	Solitary or grouped trough cross-beds
Sp	Sand, medium to very coarse; may be pebbly	Solitary or grouped planar cross-beds
Sr	Sand, very fine to coarse	Ripple marks of all types
Sh	Sand, very fine to very coarse; may be pebbly	Horizontal laminations, parting lineations
Sl	Sand, fine	Low-angle (<10°) cross-beds
Se	Sand, erosional scours with intraclasts	Poorly defined cross-beds
Ss	Sand, fine to coarse; may be pebbly	May show broad, shallow scours including cross-stratifications
Fl	Sand, silt, mud	Fine lamination, very small ripples
Fsc	Silt, mud	Laminated to massive
Fcf	Mud	Massive, with freshwater mollusks
Fm	Mud, silt	Massive
Fr	Silt, mud	Rootlets
C	Coal, carbonaceous mud	Plants, mud films
P	Carbonate	Pedogenic features

After Miall 1978.

Figure 12. Lithofacies code (after Miall, 1978).

Gm Massive clast-supported gravel

Clasts are gravel to cobble sized and sub-rounded to rounded. This facies usually displays a crude imbrication and locally is interbedded with the Gms facies. The type section of this facies is located on the north side of the Elmo

valley moraine road cut (Fig. 13) on route 28, waypoint E10 (Appendix 2).

Average clast size is between 2-5 cm.



Figure 13. Photograph of facies Gm, clast size ranges from gravel to cobble, ~2-5 cm, note pick for scale.

Gms Massive matrix-supported gravel

Matrix is a white to light tan, medium grained silt (3.5-2.5 phi) or a fine-grained sand (2.0-1.5 phi). Clasts are pebble to cobble sized, sub-rounded to rounded and locally stratified (Fig. 14). The Elmo moraine (waypoint E10), which is laterally continuous for ~1.5 km and extends vertically for ~4 m, is the only well-exposed outcrop that displays this facies.

Gms



Figure 14. (A) Massive-matrix supported gravel. Clasts are pebble to cobble in size. Meter stick for scale. (B) The Elmo moraine is the type section for the Gms and Gm facies. View to north on Highway 28.

Sm Massive sand

This facies consists of well-sorted, rounded sand (2.0-1.5 phi) that is massively bedded and contains no sedimentary structures. Dropstones or massive gravels are not present in the type section of this facies, located at waypoint E6 (Appendix 2).

Sr/ Sh Coarse- to medium- grained sand with paleoflow structures

Facies consists of lenses of moderately sorted, coarse to medium grained, sub-angular to sub-rounded sand exhibiting cross-bedding and horizontal laminations. This facies occurs locally near the spill point of the Elmo moraine in an active gravel pit and also occurs in a gravel pit in Big Arm (Fig. 8).

Fl Sandy silt

Facies mostly contains fine- to medium-grained well-sorted sand (2.0-1.5 phi) and coarse-grained white to light tan silt (3.5-2.5 phi). In the type section fine laminations and symmetrical ripples are present (Fig. 15). Sub-angular to sub-rounded pebble size clasts also are common.

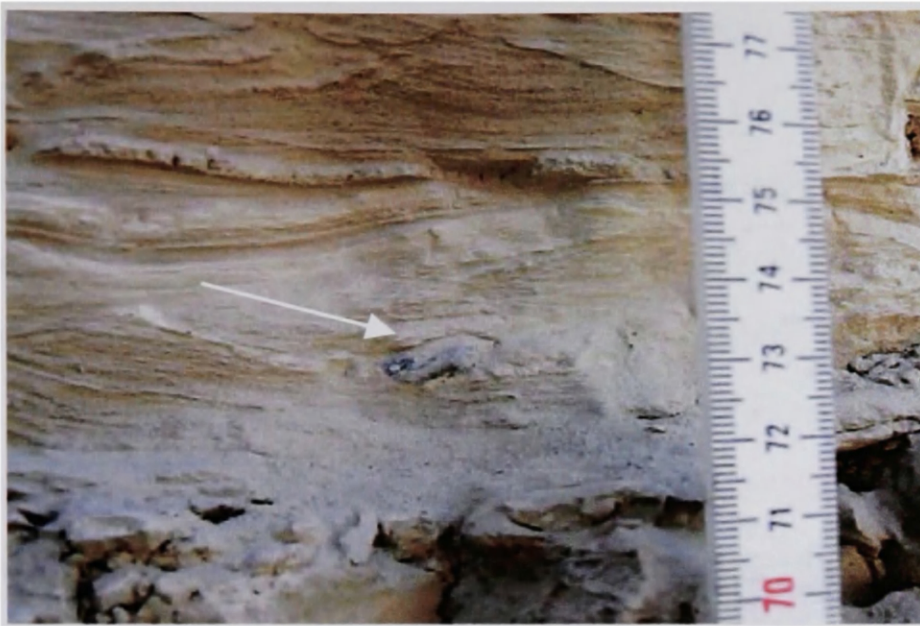


Figure 15. Photograph of facies F1 type section near Ronan Creek in Proctor Valley. Note climbing ripples within the medium-grained sand beds and the presence of local dropstones (arrow), millimeter scale.

Fsc Massive silts

Facies is dominated by laminated to massive medium- to fine-grained light pink to white silt (3.5-3.0 phi) that commonly displays soft sediment deformation around dropstones (sizes vary based on location). Facies is continuous throughout study area; the most accessible outcrop is located on route 28 (T23N R22W, base of section 23) and at the top of the Elmo moraine measured section (waypoint E10).

Map units

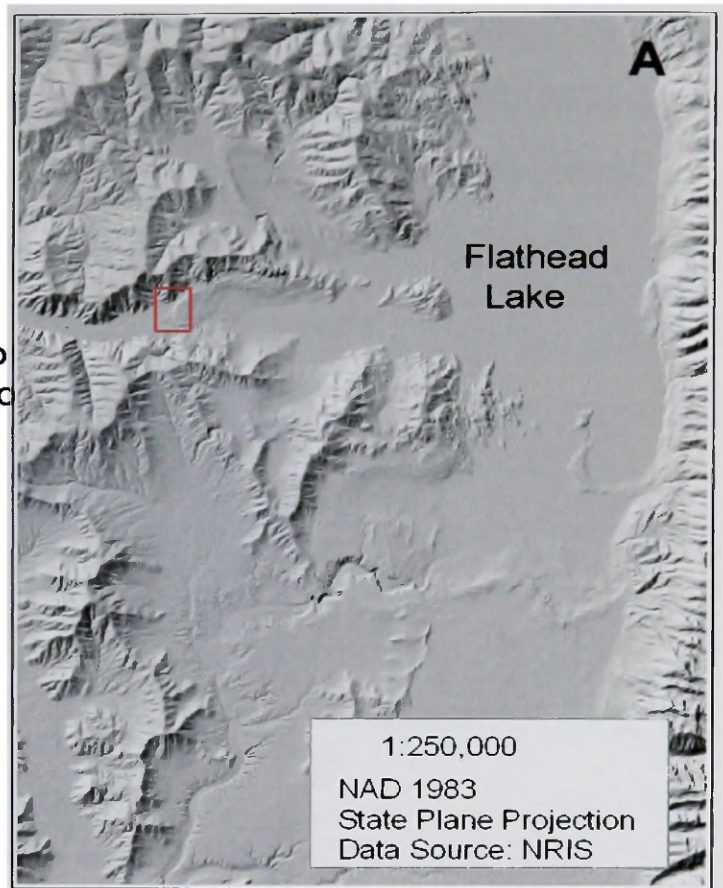
Terminal, lateral moraines and glacial till (Qgmft, Qmgfl, Qgtu)

The terminal moraines (Qgmft) deposited during the Pinedale glaciation in the Big Arm Embayment are very well preserved geomorphologically.

Hummocky, crescent-shaped landforms consisting of Gms (Fig. 16) are located in each of the three valleys. The Proctor moraine is the largest of the moraines; the crest is at ~1200 m elevation. The Proctor Valley also has the steepest relief. The Elmo Valley is characterized by lower relief and a moraine elevation of ~1000 m. The Big Arm moraine is only slightly higher at ~1100 m elevation.

Several road cut measured sections of the Elmo moraine (waypoints E10 and E11; Fig.10) display Gms and fine-grained Fsc containing highly aggradational current ripples. Lenses of Sr are interbedded within the Gms and Gm. Towards the crest of the moraine, a road cut displays a large slump block composed of Fsc. The Qgmft unit fines upward overall and is associated with climbing current ripples that suggest a west to southwesterly flow. I did not find similar sedimentary structures or stratigraphic characteristics in either the Proctor or Big Arm moraines possibly due to a lack of adequate exposure (map plate 2).

Figure 16. (A) Digital Elevation Model (DEM) of the Flathead Valley, red box highlighting the Elmo moraine.(B) Photograph of the Elmo moraine, note hummocky topography of the moraine surface.



Lateral moraines (*Qgmfly*) were identified based upon lithofacies and location relative to the terminal moraines (map plate 1). In the Proctor Valley, lateral moraines appear to be draped over bedrock along the northeast side of the valley. Boulder size angular dropstones occur commonly on the moraine surface (Fig. 17).



Figure 17. Lateral moraine (*Qgmfl*) and bedrock (*Ybe*) contact (dashed) along northside of Proctor Valley, person for scale.

The contact between the terminal and lateral moraines is not well delineated. In areas where an association with a moraine was unclear and lithofacies *Gms* was present, I defined the map unit as glacial till undifferentiated (*Qgtu*). Immediately west of the Elmo moraine there are three relatively flat-topped features (1000 m elevation) that are composed of *Gms*. I have designated these landforms as *Qgtu*; although the lithology of these landforms was similar to that of the moraines, their geomorphology was considerably different (map plate 1).

On the basis of my mapping, I infer that a spill point was cut down through the Elmo moraine during west-flowing drainage, likely associated with partial draining of glacial Lake Flathead. This area contains an active gravel pit at waypoint E15 (Fig. 18, Appendix 2). Stratigraphically, the base of the section consists of Gm lithofacies most commonly associated with the moraine. This facies displays west-dipping foresets consisting of rounded clasts (Fig. 9). Lenses of coarse-grained sand pinch out laterally into tabular beds of fine-grained white to tan silt. The entire section fines upward and is capped with a Holocene soil.

Glacial Outwash Plains (Qgo)

Located due west of the Elmo moraine (map plate 1), Big Draw is the best example of a glacial outwash plain within the Big Arm Embayment. The Big Draw begins at the spillpoint of the Elmo moraine, curves to the north around the toe of the moraine and then flows west into the valley, where it crosscuts a separate fluvial channel that is located along the northwestern side of the moraine (Fig. 19). The anastomosing fluvial plain and channel bars are clearly visible both on the aerial photos and the hillshade DEM. An observation well, the only well located in the Big Draw outwash plain (map plate 1), penetrated to a depth of 140 m without reaching bedrock. The log for this well recorded 61 m of fine-grained sand intermixed with coarse-grained sand and gravel overlain by 31 m of gravel and cobbles.

Elmo Spill Point

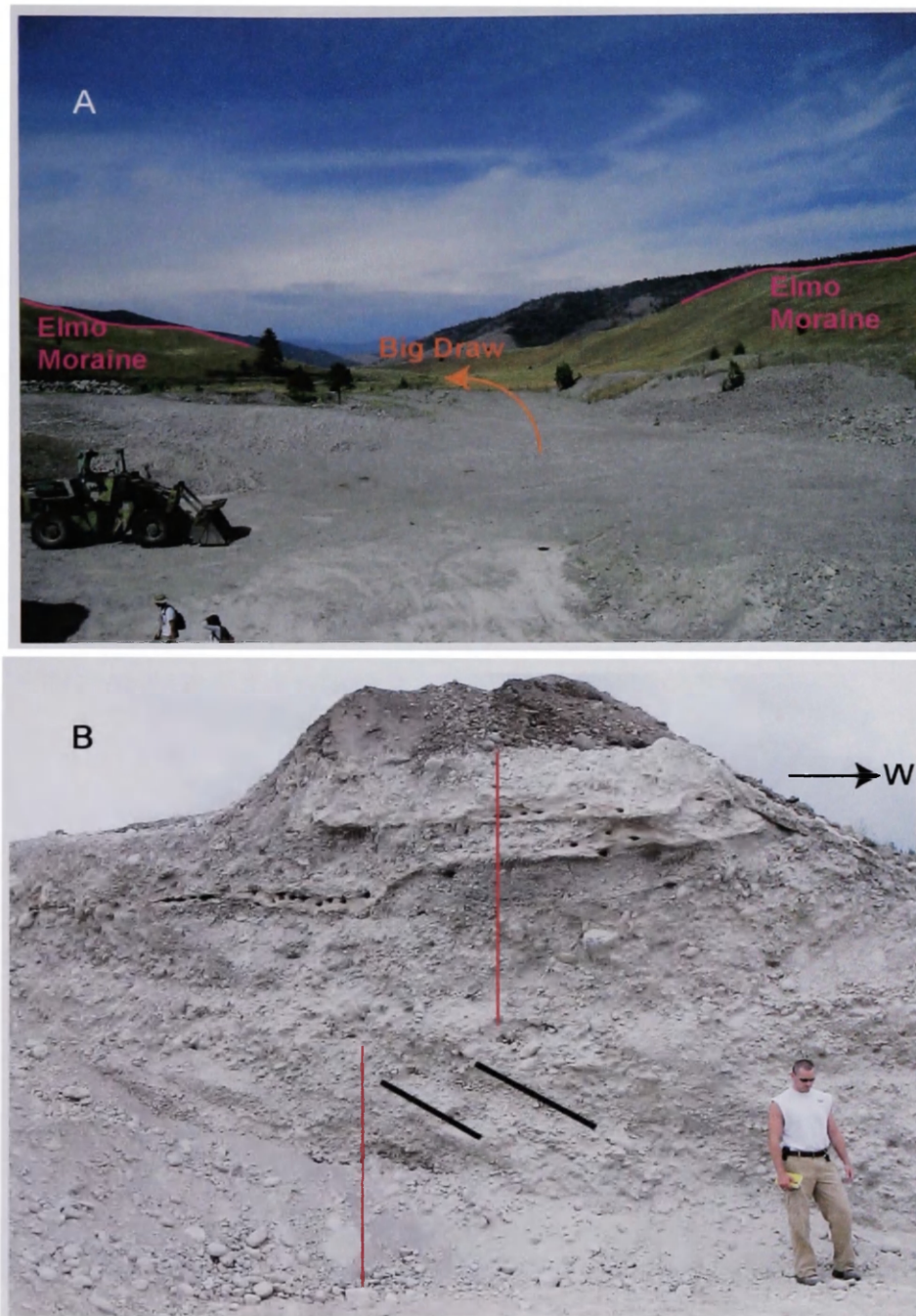
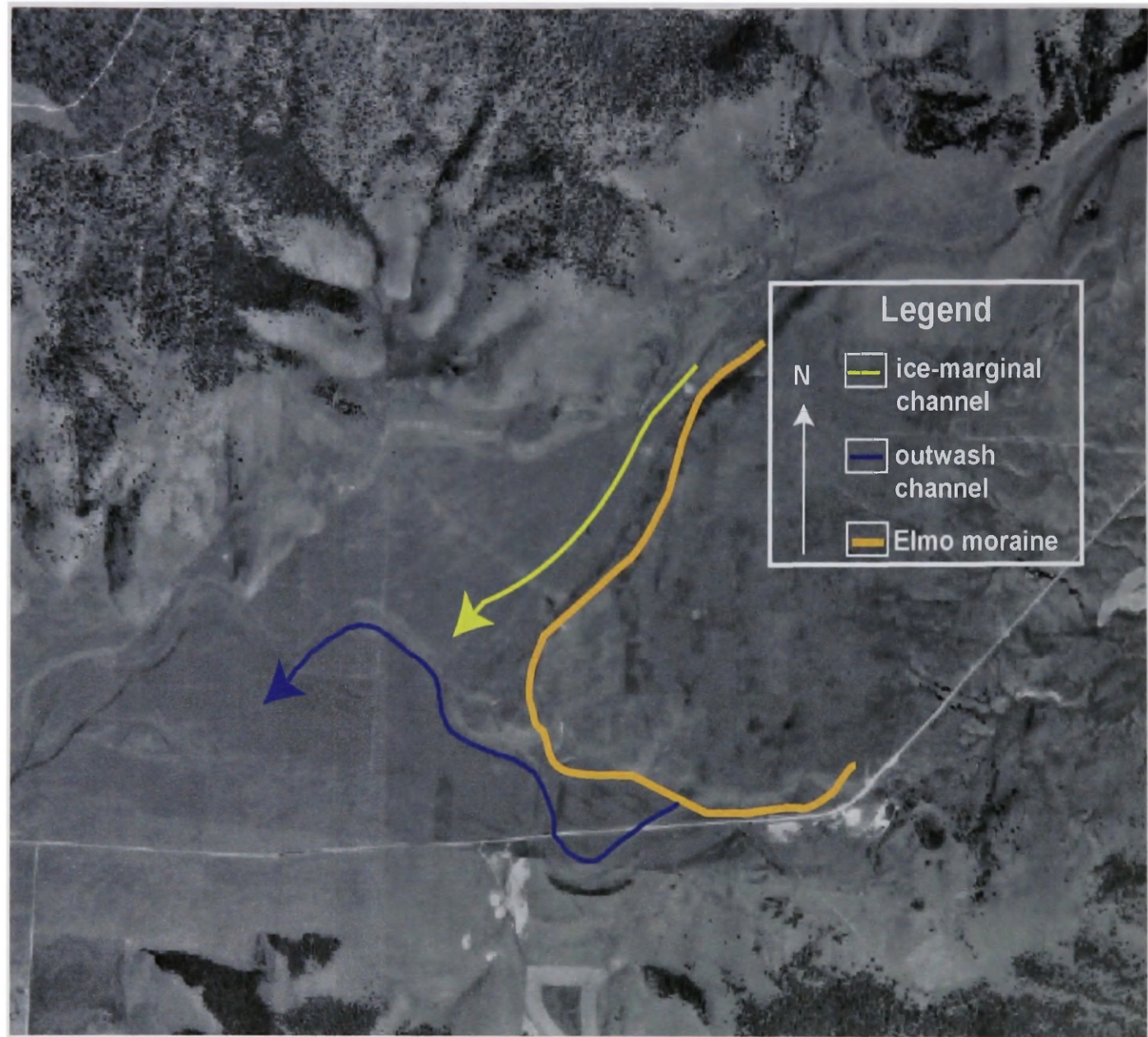


Figure 18. (A) Photograph looking due west at the crest of the Elmo moraine (pink) which was incised by proglacial waters flowing west into Big Draw (orange). (B) Photograph of a gravel pit located in the Elmo spillpoint. Note the outlined, west-ward dipping gravel foresets in black and the measured section lines in red; person for scale.

Figure 19. Aerial photograph of the Elmo moraine and Big Draw outwash plain. Note the cross-cutting relations of the two stream channels, the blue channel is younger than the yellow channel.



Two small pits located at waypoints 1 and 5, west of the inactive gravel pit on the SW side of the Elmo moraine contain (1) mostly matrix supported, rounded pebble to gravel size grains, which are locally imbricated and reflect flow towards 276° and (2) massive coarse to medium grained sands. Fluvial action is apparent southwest of this location where small-scale point bar migration is visible and foresets indicate flow to the west.

The outwash plain located west of the Big Arm moraine is bounded by bedrock and drained through a natural bedrock nickpoint at Black Gulch (map plate 1). Groundwater wells drilled in the outwash plain penetrated 91 m of gravel with a silty loam cap (pers.comm. with owner Mike Grende, 2004). A small wetland-designated area defines the water table (map plate 1) and ephemeral springs still produce surficial flow through the Gulch. Low relief hills are apparent within the central outwash plain. Relatively well-sorted, rounded gravels cap these hills. I observed no evidence of eolian sedimentation. The southern portion of the outwash plain is characterized mainly by facies Fsc, this area lacks the rounded cobbles found in the northern portion. Flat-topped terraces are visible along the north side of the outwash plain; these terraces are cut by fluvial channels near the toe of the Big Arm moraine (Fig. 20).

The Proctor moraine terminated at the shoreline of proglacial Lake Mary Ronan (present day Lake Mary Ronan, LMR) until the retreat phase. Ronan Creek is the present drainage for LMR and flows south out of the lake before turning northeast and cutting through a rather large incised canyon, in which massive accumulations of glacial diamict are draped on top of bedrock.

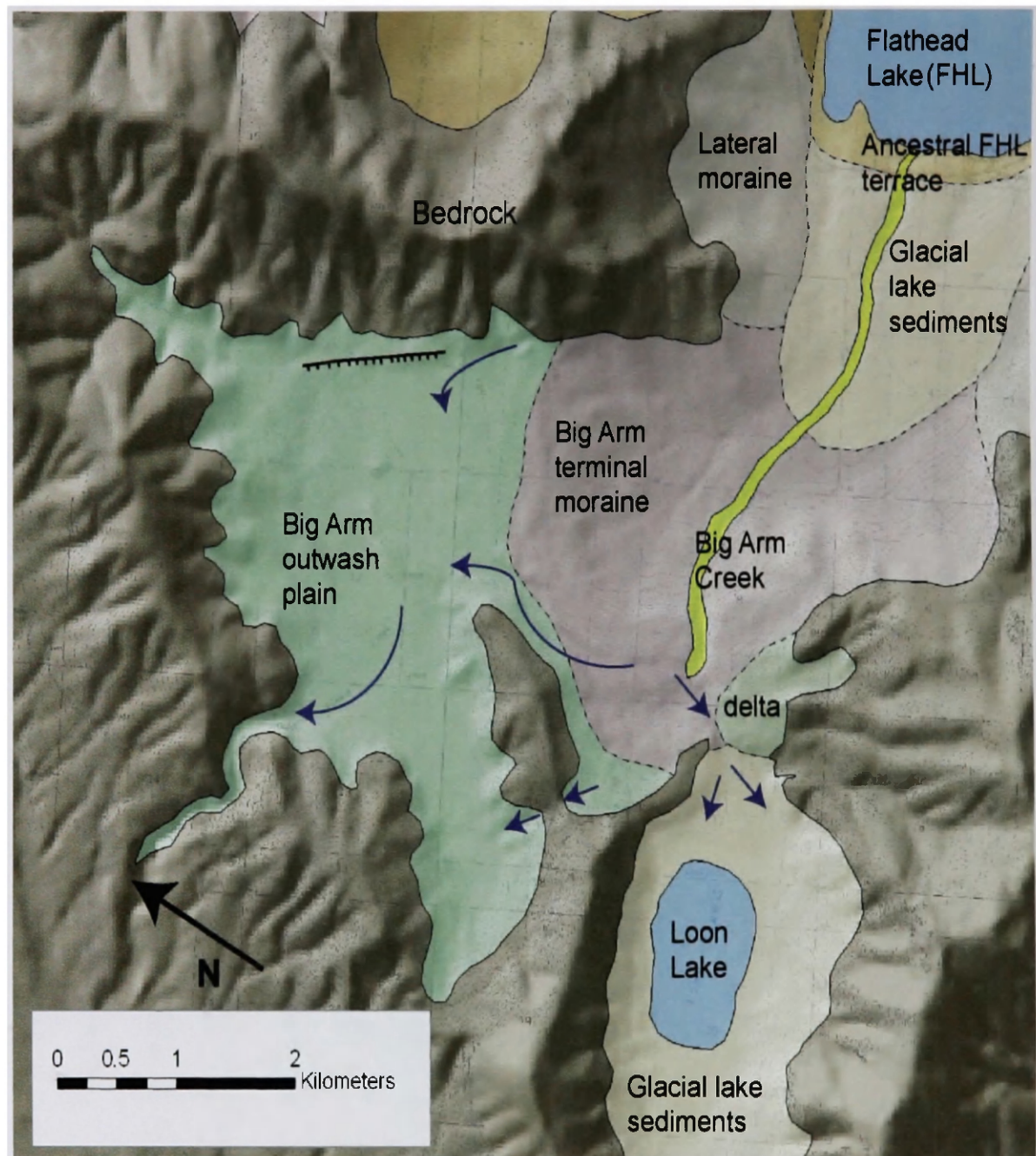


Figure 20. Flow directions(blue arrows) of glacial outwash in the Big Arm Valley, fluvial cut terrace outlined in black.

Glacially influenced Gilbert-style deltas (Qgde)

Gilbert-style deltas typically contain three main architectural components: (a) horizontal topset beds, consisting of fluvial sediments; (b) downstream inclined foresets, deposited due to sediment gravity flows along the delta front; and (c) horizontal bottomsets, deposited by underflows (Benn and Evans, 1998). A small Gilbert-style delta is preserved at the mouth of Ronan Creek (map plate 1), suggesting that this drainage once emptied into a proglacial Lake Flathead that was dammed in Proctor Valley during glacial retreat. Stratigraphic sections measured in drainages near this delta contain abundant paleocurrent indicators in the form of medium to well sorted fine-grained sand exhibiting crossbedding and climbing ripples. These overlie massively bedded glacial silt with soft-sediment deformation around local and exotic dropstones (Fig. 11). A second and better-developed Gilbert-style delta is preserved where south flowing Dayton Creek enters the main floor of the Proctor Valley, waypoint PR6 (map plate 1). I infer this second delta to have formed as a result of the draining of the Upper Dayton Creek drainage system, which merges to form Dayton Creek in the southern part of Proctor Valley. Deltaic sediments consist of stratified gravel, graded beds of silt and sand, and steeply east-dipping (~90 azimuth) foresets (Fig. 21). Each foreset consists of sand and gravel, with particularly coarse gravel occurring in grain-supported pods. These sediments are interpreted as grain flow deposits that were deposited on the active slope of the Gilbert-style delta (Nemec, 1990). The topset beds of this delta have been removed due to active mining of gravel.

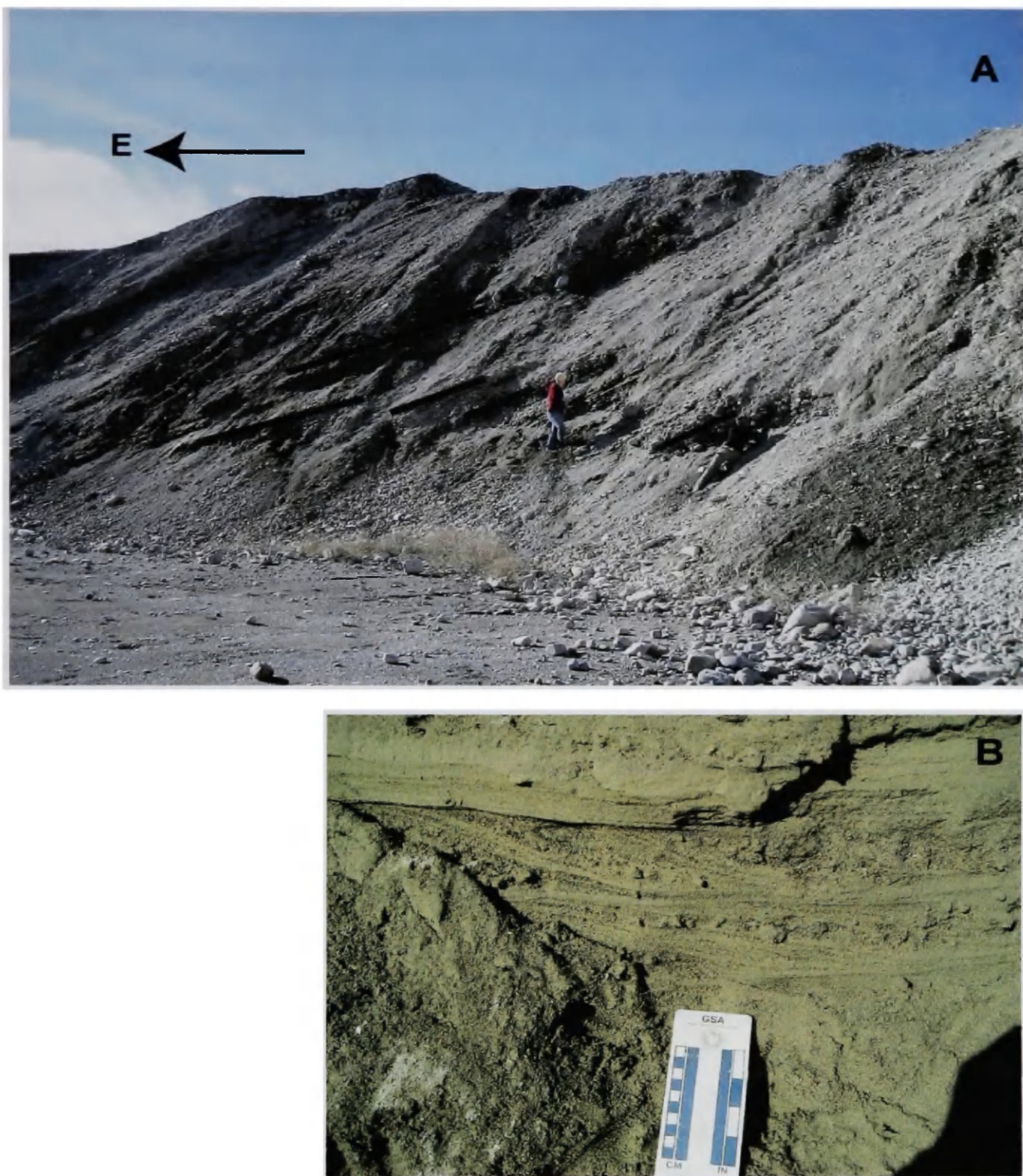


Figure 21. (A) Photograph of the Dayton Creek delta, note the eastward dipping gravel foresets, person for scale. (B) Close-up of lower beds of coarse-grained sands displaying shallow trough crossbeds.

An active gravel pit located along the northwest side of Big Arm Valley, waypoint BA 25 consists of facies similar to the Dayton Creek delta but at a smaller scale. Measured sections from this area indicate that the most common facies are Gm, Sp, and Sh (Fig. 8). Measured clast lineations and sub-critically climbing current ripples indicate flow into present day Flathead Lake (122 azimuth).

Based upon outcrops he viewed at a gravel pit, Smith (1966) mapped a deltaic flat, three-fourths of a mile in length, extending into the Loon Lake Basin. The gravel pit described by Smith (1966) is now largely gone and is covered by a well-developed Holocene soil horizon. I defer to Smith's description of the sediments, which were defined as till overlain by a couple meters of stratified gravel and sand (Smith, 1966). Geomorphologically, the unit is relatively flat topped and slopes towards Loon Lake, consistent with a Gilbert-style delta interpretation (Fig. 20).

Glacial Lake sediments (Qgl)

Glacial lake sediments were identified based on the lithofacies Fsc, when present; laminations typically display an average thickness of ~3 cm. In drillers' logs, this unit is recognized by its silt-dominated lithology and the production of almost no groundwater (Smith, 2004).

Within the Elmo Valley, Qgl sediments are found at lower elevations (~950 m to lake level) predominantly within creek drainages. The Elmo moraine measured section (Fig. 10) contains lake sediments with associated climbing current ripples that indicate a paleoflow direction to the south or southwest. The

community of Elmo is built upon lake sediments. No large packages of lake sediments are present in the well log for Big Draw or exposed at the surface, although faint shorelines were observed at an elevation of ~1600 m on the hilltops south of the Elmo moraine crest. A notable lack of glacial erratics and dropstones characterizes the Qgl of Elmo Valley.

In Proctor Valley several drainages were dammed during deposition of the morainal sediments. These include Lake Mary Ronan, the upper Dayton Creek drainage, and Big Meadows (Smith, 1966). Smaller glacially scoured lakes (Skaggs and Bow lakes) are located along the northern side of Proctor Valley, upslope from the well-developed delta complex (map plate 1). Lithologically the sediments of these small lakes and meadows are similar to the Elmo Valley lake sediments. Sub-angular to sub-rounded dropstones are more common, presumably because of the proximity to eroded alpine glacial drainages. As in the Elmo Valley, the majority of Qgl sediments are found in creek drainages. A section of exposed sediments in Ronan Creek was measured (Fig. 11) and displays ~ 1 m of laminated silts with soft sediment deposition and associated pebble- to boulder- sized dropstones. Lenses of Sr and Sh are interbedded throughout the section. The town of Dayton is also situated on lake sediments.

I interpret that the Big Arm moraine dammed a proglacial lake in the bedrock-confined Loon Lake basin (map plate 1). Loon Lake is an ephemeral lake that typically is dry most of the year. There are no obvious glacial erratics cropping out around the surface in the Loon Lake Basin.

Ancestral Flathead Lake sediments (Ql_{kf})

As the Flathead Lobe was retreating, a large proglacial lake was dammed against the ice margin and the terminal moraines in the Flathead Valley. Around the western perimeter of the lake, a wave-cut terrace is evident that locally runs parallel with Hwy 93 and is located at 902 m elevation, approximately 30 m higher than present day lake level (map plate 1). Shorelines on the north side of the Polson moraine occur at the same elevation as this terrace. Exposed sediments in this terrace commonly consist of reworked Fsc and Sm.

Kame Terrace

Along the northeast hills of the Proctor Valley, a prominent kame terrace cuts the cliffside where the FHL came into contact with bedrock and deposited a lateral moraine (Fig. 22). This kame terrace is approximately 6 km long, ~10 m across at its widest point and obtains a surface height of 1200m.

Topographically, the terrace is very flat with highly eroded, steeply dipping slopes. There is an obvious bench located beneath the terrace around 975 m that is similar in lithology to the terrace and probably relates to slumping and alluvial fan development following glacial retreat. Lithologically, the terrace is composed of a tan to whitish, coarse-grained silt to fine-grained sand matrix littered with gravel to cobble, sub-angular to sub-rounded clasts (Fig. 22).

Overall, the sediments are poorly sorted and incorporate locally derived angular boulder size clasts that display striations.



Figure 22. (A) Photograph of the kame terrace (arrow) located on the north side of the Proctor Valley. (B) Close-up of the sediment found on top of the flat terrace, pencil for scale. (C) Clast count conducted on the slope of the terrace, note the poor sorting and range of clast sizes.

Subglacial bedforms

Along the Proctor valley floor, a group of east-west orientated, parallel ridges are prominent on DEMs and aerial photos of the Proctor Valley (Fig. 23). Cross-sectional road cuts through these landforms consist of the facies Gms (Fig. 23) and locally display clasts with an average long axis orientation of $\sim 207^\circ$. I tentatively interpreted these structures to be large-scale basal ice sheet bedforms, based on their morphology and sedimentology.

The three most common types of longitudinal subglacial bedforms are eskers, drumlins, flutes, and megaflutes (Menziés and Rose, 1989). The lack of sand facies and non-sinusoidal morphology of these landforms are inconsistent with an esker interpretation. Drumlins are identified based upon the standard teardrop morphology that originates from ice flow direction. The bedforms identified in the Proctor Valley do not display this distinct drumlin morphology; rather the bedforms tend to widen in the direction of flow (i.e., towards the NW) (Fig. 24). Drumlins that are continually elongated throughout deposition will commonly grade into megaflutes (Benn and Evans, 1998). Glacial flutes typically consist of subglacial till, generally occur in groupings of subparallel ridges in glacial environments, and can form downglacier from lodged boulders or clasts, though this is not a requirement (Benn and Evans, 1998). I believe these landforms most closely resemble megaflutes, re-worked as subglacial streams scoured the underlying till during retreat of the FHL from the Proctor Valley.

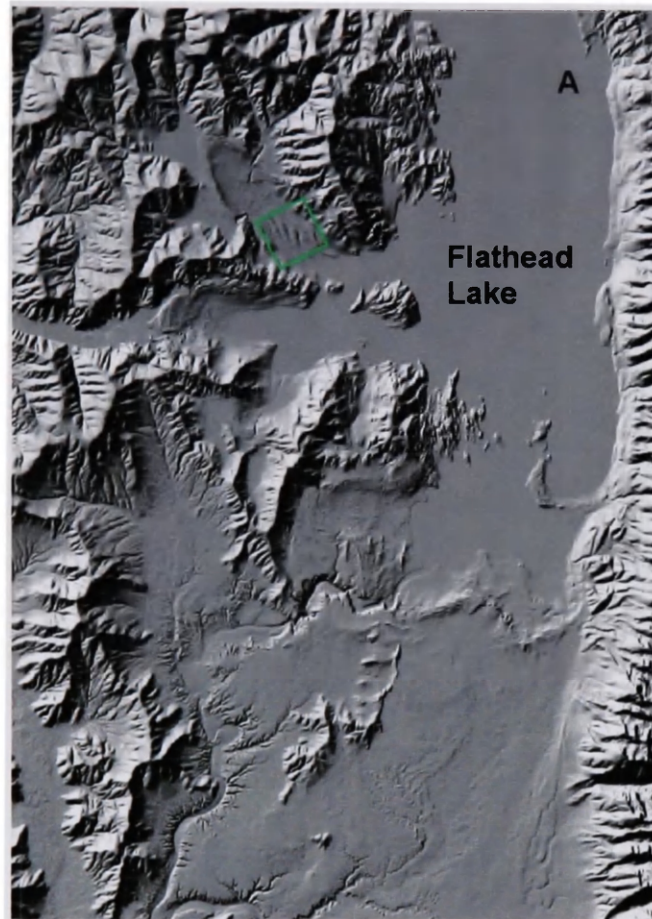


Figure 23. (A) DEM of Flathead Valley, green box indicates location of subglacial bedforms. (B) Photograph looking across the Proctor Valley, note linear ridges highlighted with the black lines. (C) Cross-sectional cut horizontally through one of these linear ridges, note the poor sorting of the gravels and range of clast size.

Proctor Valley Cross-section

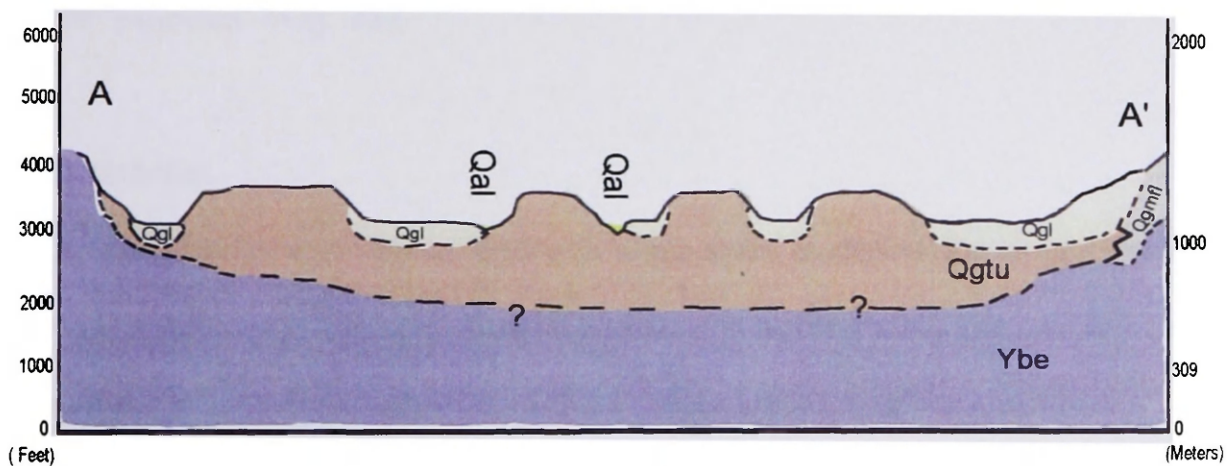
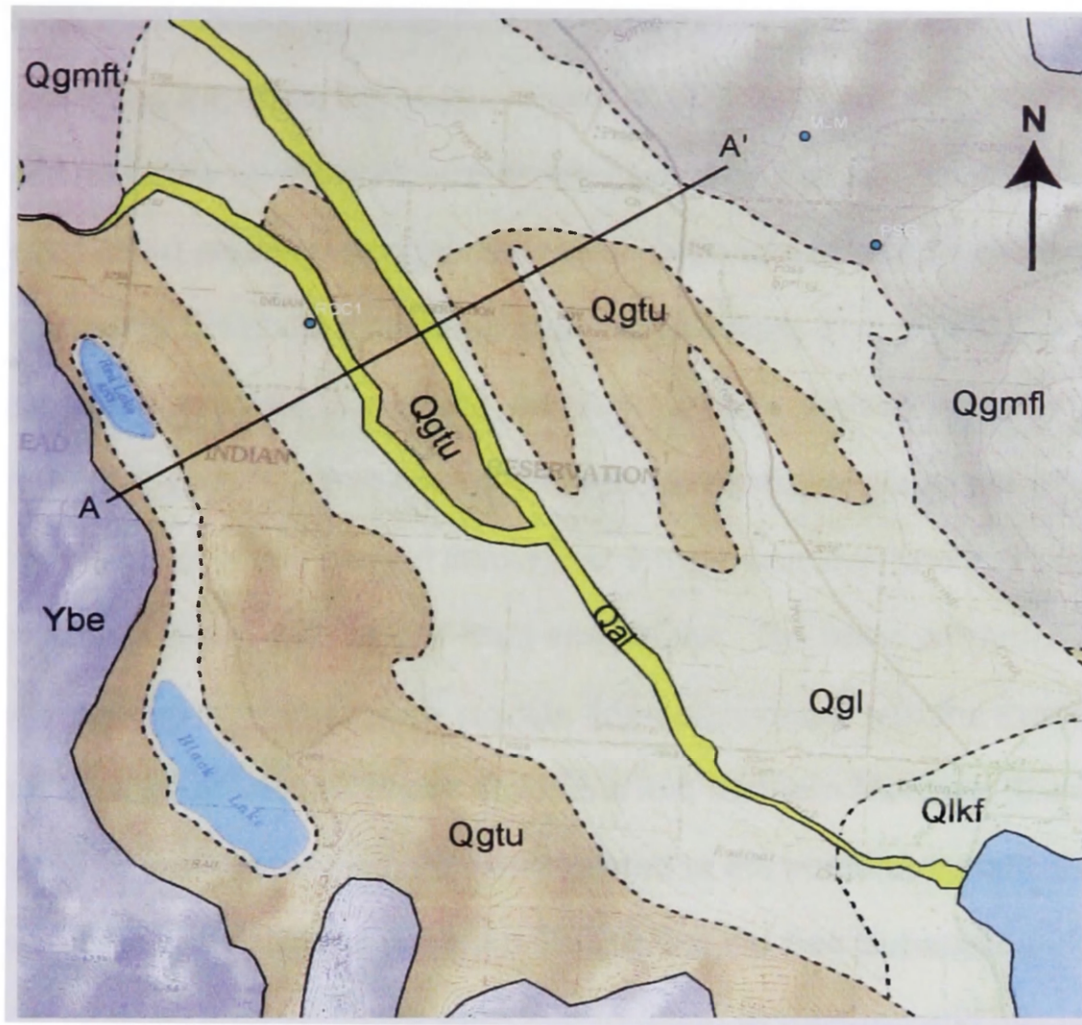


Figure 24. Geologic map and cross-section of the Proctor Valley sub-glacial bedforms.

Clast Provenance

Clast counts were conducted in each of the major gravel pits within the three valleys and along the kame terrace in Proctor Valley. A 1x1 m area was designated and then sampled at a centimeter spacing (Fig. 22). The kame terrace clast count revealed a large number of carbonate and siltite clasts (Fig. 22). The majority of the clasts located near the spill point of the Elmo moraine are composed of quartzite, carbonate, and argillite likely derived from the Belt Supergroup (appendix 1). Sub-rounded to rounded volcanic clasts are also present and consist of two distinct lithologies: a felsic volcanic lithology and a mafic volcanic lithology with calcite-filled amygdules. The felsic volcanics are most likely derived from porphyritic rhyolite flows associated with the Purcell Lava (Fig. 3) of southeastern British Columbia and northern Montana (Evans et al., 2002). The mafic volcanics are either related to the numerous mafic dikes and sills that occur throughout the lower Belt unit of the Belt Supergroup (Fig. 3). Overall, in all three valleys, clasts were sub-rounded to rounded and glacially striated or “plucked” (Fig. 22).

Glacial Striations

Glacial striations in situ on bedrock were used to define the upper ice limit within the Big Arm Bay (Fig. 25). Bedrock outcrops surrounding the smaller lakes and elsewhere along the north side of the Proctor Valley display striations scoured by glacial movement.

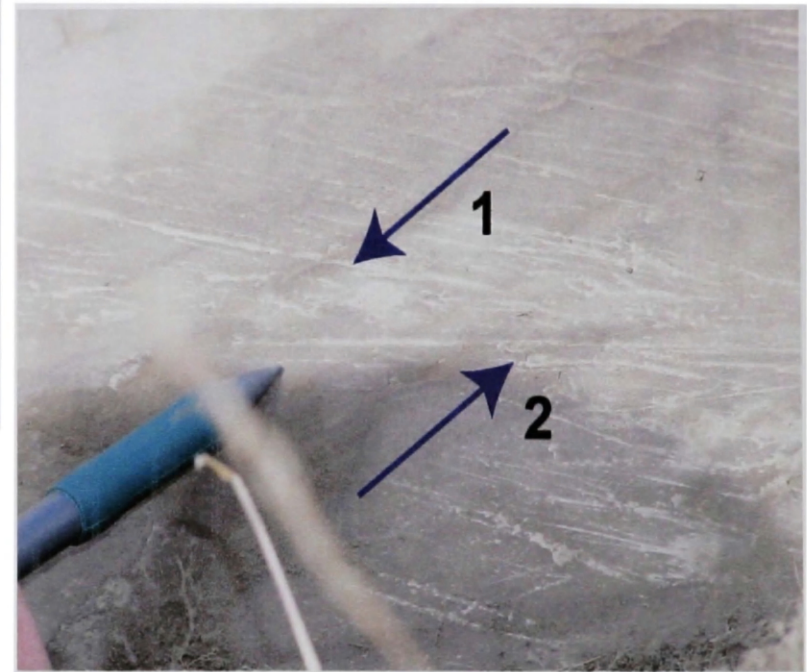
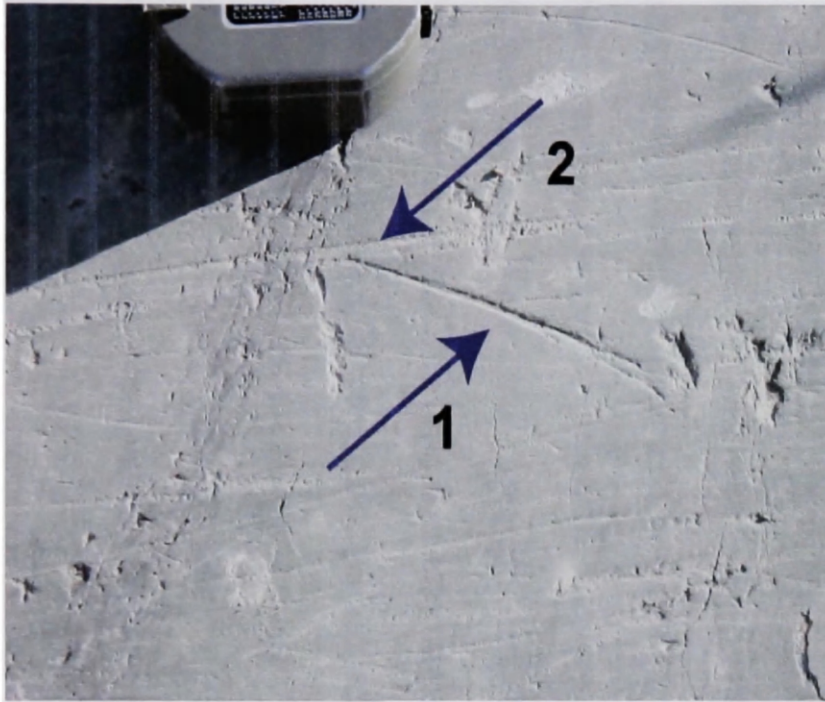


Figure 25. Glacial striations located along bedrock knobs throughout the Big Arm Valley, note the apparent cross-cutting of the two distinct directions, pencil and brunton for scale.

Typical striae azimuths range from 270° to 35° (map plate 1). Further south, the Big Arm moraine is constrained on its south side by bedrock hills that also display abundant glacial striae. Cross-cutting striations are often observed atop the major hillsides, likely due to advance and retreat of the glacier and complex sliding dynamics (Fig. 25). The majority of striations in the Big Arm Embayment display a SW-NE direction except in the northern Elmo Valley (hogbacks located due east of Chief Cliff) where the main lineation is E-W (Fig. 24).

Hydrogeology

The water table for the low-lying valley communities such as Dayton, Elmo, and Big Arm (Fig. 1) is shallow due to the proximity of modern Flathead Lake. The producing horizon (shallow alluvium map unit of LaFave et al., 2004) is about 30 m thick and consists mainly of rounded gravels and sand located throughout the shallow alluvium and in sporadic Gm lenses (Fig. 26). GLM sediments, categorized in this study as Fsc, are considered to be aquitards due to their low permeability. Tills or morainal units (Gms) are commonly described in drillers' logs as clayey or silty gravel or clay-bound gravel that produces almost no groundwater. Lenses of sands and clast-supported gravels located within the till characteristically produce groundwater (Smith, 2004). The Proctor Valley has active surface streams, although, all three valleys draw groundwater from fractured bedrock, based upon well log data (cross-section B-B'', plate II).

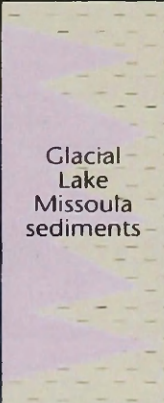
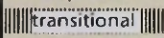
Period	Epoch	Kalispell, North Fork, Coram, Smith, Swan, and Flathead Lake Perimeter Subareas		Mission, Little Bitterroot, Jocko, Irvine Flats, and Camas Prairie Subareas	
Quaternary	Holocene	Shallow alluvium	Sand and gravel with minor silt and clay within modern stream valleys and in broad alluvial and eolian sheets.		<p>Brown and gray beds of silty and clayey gravel (diamicton), laminated silt and clay, and minor amounts of sand and gravel. Bedding along canyon walls of the Flathead River from Kerr Dam downstream to near Moiese is laterally continuous. Deposition is interpreted to have been in Glacial Lake Missoula (Levish, 1997); some diamictons (till) in Polson moraine and Valley View Hills were deposited by glacial ice; some till may also occur in subsurface in the Mission valley.</p>
		Ancestral Flathead Lake deposits 	Brown and gray, laminated, calcareous fine sandy silt, clayey silt, and minor clay; upper surfaces are mostly broad and even; deposited from suspension in a lake that was initially pro-glacial; exposed as the lake sill was downcut and postglacial erosion occurred.		
	Pleistocene	Glacial-lake deposits			
		Till	Gravel and boulders in a matrix of gray and brown dense sand mud (diamicton); some stratified sand and gravel deposited by, or near, glacial ice; clasts are typically rounded and subrounded metacarbonate, quartzite, argillite, and diorite; more resistant clasts are commonly striated; forms cores of many glacial landforms such as drumlins and moraines.		
		Deep alluvium	Brown, yellowish brown, and gray stratified coarse-grained sand and gravel conglomerate; rare calcium carbonate cement; clasts of quartzite, argillite, and metacarbonate.		
<i>local or basin-wide unconformities</i>					
Tertiary	Eocene-Miocene(?)	Tertiary sedimentary rocks and some volcanic rocks	<p>Sedimentary rocks: Brown and orange medium and coarse-grained pebbly sandstone; pebble and cobble conglomerate; carbonaceous shale with carbonized wood; gray, yellow, and orange mudstone; and orange clayey gravel (diamicton). Gravel clasts of argillite, quartzite, and siltstone are mostly well rounded. Sandstone and conglomerate beds have channelized, erosional bases. Diamicton unit locally infills fractures in Belt Supergroup bedrock.</p> <p>Volcaniclastic rocks: sandstones, conglomerates, breccias, diamictons, and tuff (compacted deposit of volcanic particles) that contain small to large percentages of Belt Supergroup gravel- and sand-sized particles (Lange and Zehner, 1992).</p>		
<i>unconformity</i>					
Proterozoic		Belt Supergroup	Numerous stratigraphic units composed mostly of metamorphosed siltstones, carbonates, and quartz sandstones (Johns, 1970; Winston, 1986; Harrison and others, 1986, 1992) and minor amount of igneous rocks (McGimsey, 1985). Most bedding thicknesses range from less than 1 inch in metasilts to a few feet to tens of feet in metacarbonates and quartzites.		

Figure 26. Hydrogeology of the subsurface of the Flathead Valley (from LaFave and Smith, 2004).

Smith et al., (2004) defined Tertiary basin-fill sediments as having good aquifer potential, although based on well-log reports and associated cross-sections (plate II), the presence of Tertiary sediments in Big Arm Embayment cannot be demonstrated.

Interpretations and Discussion

Lithofacies Classifications

For the purpose of this study, terminal and lateral moraines (*Qgmft*, *Qgmfl*) were differentiated based on facies and sedimentary structures present along with associated geomorphology. I interpret the Elmo moraine as being deposited in a sub-aqueous environment due to the stratification of the gravel (*Gms*), the subaqueous climbing ripples and the overall fining upward sequence of the sediments (Krzyszowski, D., 2002). In the absence of a distinct morainal geomorphologic association, lithofacies *Gms* and *Gm* were mapped as *Qgtu*, glacial till undivided.

My separation of *Qgtu* as a distinct map unit is justified by the genetic definition of till as “sediment that has been transported and deposited by or from glacial ice, with little or no sorting by water” (Shaw, 1985). Occurrences of *Qgtu* within the map area all share the following characteristics: 1) they are located adjacent to or at the distal end of morainal units; 2) on the surface they display well-rounded exotic clasts, and 3) they are found at or above elevations associated with glacial striations and tend to form a relatively thin drape over the scoured bedrock (map plate 1). The notable exception to these general

observations is located west of the Elmo moraine and where three flat-topped landforms (~1000 m across) display facies Gms (Fig. 27). In this study, these landforms were also mapped as *Qgtu*. An old gravel pit dug into one of these landforms (waypoint Educk) is highly eroded, but boulder to pebble sized, sub-rounded to rounded clasts are present in a coarse-grained silt matrix. Clasts are pockmarked and striated. Smith (1966) stated that these flat-topped landforms were deltas that drained into GLM when the FHL was inundating the Elmo Valley. I agree that the landforms display a delta-topography (flat-topped); however the exposures lack the correct lithofacies (Sm, Sr/Sh) and architecture needed to be interpreted as a delta dominated system (Fig. 27).

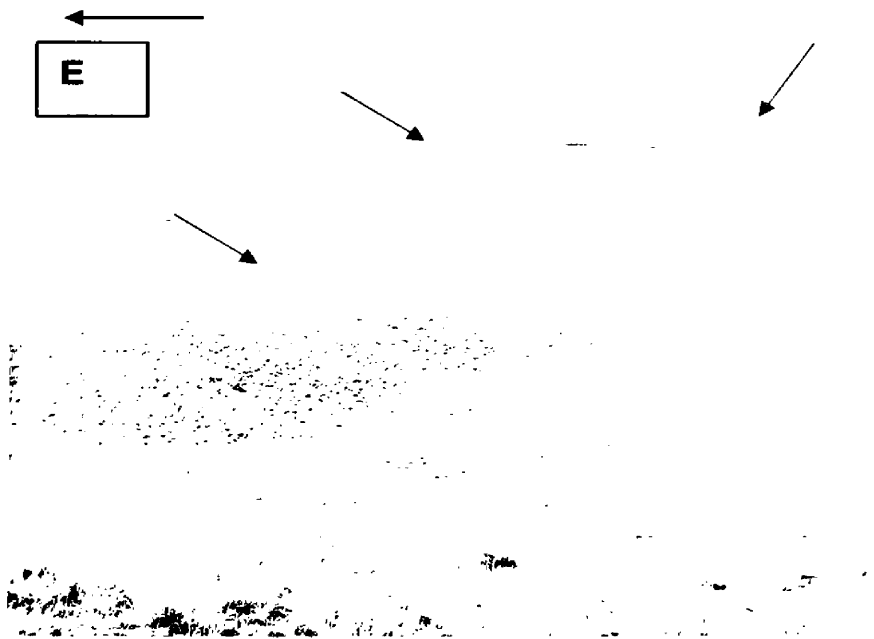


Figure 27.

Photograph looking south across the Big Draw at the three undefined landforms (red arrows), note the flat tops and equal elevations.

A second hypothesis for the deposition of these features is that they represent a remnant moraine from an older glaciation, although this cannot be demonstrated

due to the lack of absolute dates within the field area. A third hypothesis is that these features represent sub-aqueous debris flow fans, but this would require the sediments to coarsen towards the distal end of the landforms and such gradation is not seen. Powell and Domack (1995) introduced the term *grounding-line wedges*, which refer to dipping diamicton beds overlain by horizontal sheets of subglacial till. This term replaced the prior terminology of *till delta* thereby avoiding any association with base level (Benn and Evans, 1998). The landforms in the Elmo Valley are apparently cross-cut by the Elmo Valley terminal moraine as well as by fluvial outwash channels. I infer that prior to these events these landforms were continuous across the Big Draw. Further fieldwork is required in order to adequately interpret these features.

Kame terrace deposition

Kame terraces are defined as a “terrace-shaped ridge consisting of stratified sand and gravel formed as a *glaciofluvial or glaciolacustrine* deposit between a melting glacier or a stagnant ice lobe and a higher valley wall or lateral moraine, commonly pitted with kettles and containing an irregular ice-contact slope” (Bates and Jackson, 1984). Due to its lithology and geomorphology I suggest that the Proctor Valley kame terrace was deposited in a glaciofluvial environment in which an ice marginal stream flowed over active lateral moraine deposits. Smith (1966) identified the same terrace in his study; he attributed the deposits to sedimentation in meltwater streams that terminated in a

small deltaic flat on the north side of the Proctor Valley moraine. I found no geomorphic evidence of deltaic features in this area.

Aquifer potential

Due to increasing development within the Big Arm Bay community, aquifer potential and the lateral extent of water-bearing units has become an important issue. Cross-sections (plate 2) show the extent of the glacial sediments throughout the three valleys. The outwash sediments and ancestral Lake Flathead terraces likely are the most productive aquifers due to the fact that they contain abundant sand and gravel lithologies. The morainal units and glacial lake sediments tend to be poor aquifers unless the well penetrates a gravel lens within them. Bedrock fractures also are locally producing aquifers, and many people in the Big Arm Valley benefit from them. The Elmo Valley derives much of its water from an artesian well which produces ~ 100 gpm and is located in the sandy facies near the current lake shore.

Deglaciation of the Big Arm Embayment

During the Pinedale, the Flathead Lobe deposited terminal moraines in each of the three valleys of the Big Arm Embayment. The Proctor moraine, in effect, dammed Lake Mary Ronan (LMR) which during the Pinedale was considerably larger than present. Supraglacial flow and subglacial melt are attributed to the increase in size of the lake, which at that point included Big Meadows, located south of the moraine terminus. Presently, Big Meadows

consists of a dry lakebed that incorporates the meandering Ronan Creek, the drainage outlet for LMRO. At the southern edge of Big Meadows is a large incised canyon that displays glacial Lake Ronan sediments overlying bedrock. Ronan Creek drains into the Proctor Valley through a remnant Gilbert-style delta, the “Ronan Creek Delta” of Smith (1966), before joining Dayton Creek further down the valley. This drainage path likely was formed during deglaciation of the Proctor valley. Smith (1966) offered an alternative interpretation, suggesting that Lake Mary Ronan drained through a channel that cut Chief Cliff and became an outwash channel for the Elmo Valley, when glaciers were still present in the valley. I observed no fluvial cut channels or rounded exotic clasts along the bedrock terrace between Black Lake and Chief Cliff (map plate 1) that would support this hypothesis.

Several smaller glacial lakes (present day Grass and Basin meadows, Skaggs and Bow Lakes, map plate 1) were formed on the northern side of the Proctor glacier, where lateral moraine and ice came into contact with bedrock. Along the southern edge of the Proctor moraine, Black and Red lakes were joined to form one larger lake. Due to a lack of glacial sediments along bedrock southwest of these lakes, I hypothesize that this lake basin was eroded into bedrock during an earlier glaciation (early stage of Pinedale or late Bull Lake). Presently Black Lake and Red Lake are split by a topographic high and have no drainage outlets.

The Big Arm moraine dammed two pro-glacial lakes, one formed due to the terminal advance of the glacier (glacial lake Big Arm) and the other formed

due to the inundation of the Loon Lake basin (pro glacial Loon Lake). Alden (1953) inferred the existence of an older remnant moraine located within the glacial lake Big Arm outwash plain. A field check of this area revealed small bedrock-cored hills covered with well-sorted rounded outwash gravels. Several outwash channels are visible within the Big Arm Valley (Fig. 20); one is located on the northwest side of the moraine and was probably cut by glacial melt waters that fed the outwash plain. Another well-defined channel was formed between the base of a large bedrock-based hill and the southern extent of the Big Arm moraine (Fig. 20) and was likely cut by a combination of flows from the draining of proglacial Loon Lake.

The terminal limit of the Flathead Lobe is expressed topographically as the Polson moraine, a large hummocky landform stretching from the Mission Mountains to present day Kerr Dam (Fig. 2). The depositional environment of the Polson moraine is considered to be sub-aqueous based on the presence of abundant sub-aqueous climbing current ripples observed in exposures of the moraine in the Redi-Mix gravel pit along Highway 93 (Hofmann and Hendrix, 2004). Shorelines related to GLM lake levels are evident on the Moise and Valley View Hills south of the Polson moraine. The shorelines represent wave-cut terraces that define lake high-stands throughout the Pleistocene. Shorelines, interpreted in this study to be a remnant of GLM, are faint but apparent at an elevation of 1160 m along the bedrock hills above of the terminus of the Elmo moraine. The geomorphologically well preserved nature of the Elmo outwash plain and the subaqueous nature of the Elmo moraine suggest that GLM drained

prior to the retreat of the FHL and formation of proglacial Lake Flathead (GLF), formerly defined by Smith (1966) as Glacial Lakes Elmo, Dayton, and Big Arm. I infer that the Dayton creek delta of Proctor flowed into GLF, as suggested by the eastward dipping foresets. As deglaciation continued, GLF levels rose due to the increase in meltwaters and began to cut through the morainal sediments in key areas. Flow directions indicated by aggrading current ripples measured on the top of the Elmo moraine (waypoint id E11) suggest flow towards the southwest. Climbing ripples and westward dipping foresets observed in the active Elmo gravel pit (Fig. 9) suggest that there was a major spill point cut by GLF near the terminus of the Elmo moraine (Fig. 18). The outwash plain west of the Elmo moraine clearly defines the remnant fluvial channel system that drained from the spillpoint and clearly cross-cuts an older fluvial channel (Fig. 28). I infer that this older fluvial channel, which Smith (1966) defined as the “Elmo Spillway” was formed from supraglacial and subglacial flow when the glacier was in its terminal position. The channel exhibits point bars and flow paths that suggest a westward flow direction. Ice-rafted debris litters the channel floor; some angular clasts are almost 1 m across. One terrace located near the head of the channel is covered with highly angular, local bedrock boulders seemingly plucked out of the surrounding bedrock.

The approximate 1000 m elevation of the Elmo moraine spill point is higher than the southern drainage outlet for the Flathead Lake system, located in the lower Flathead River Canyon close to the construction site for Kerr Dam. I hypothesize that the Elmo spill point actively accommodated draining of the

proglacial lake Flathead system until the lake level fell below the Elmo spill point and it was abandoned. This scenario was first proposed by Smith (1966) who stated that "Glacial Lake Elmo" was controlled by the elevation of the outlet. Following, the Polson spill point accommodated continued lowering of the Flathead Lake level to its modern position (Fig. 29).

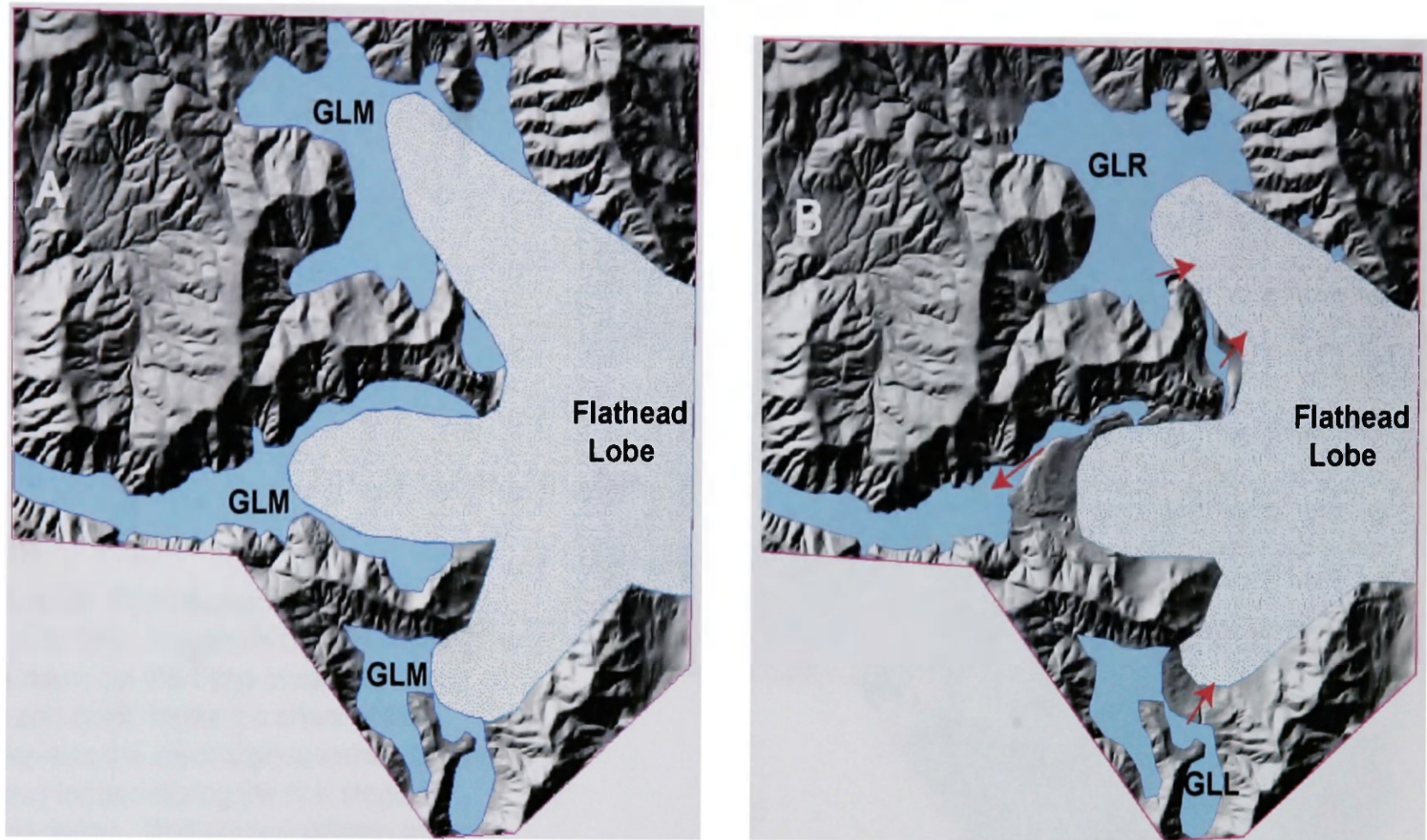
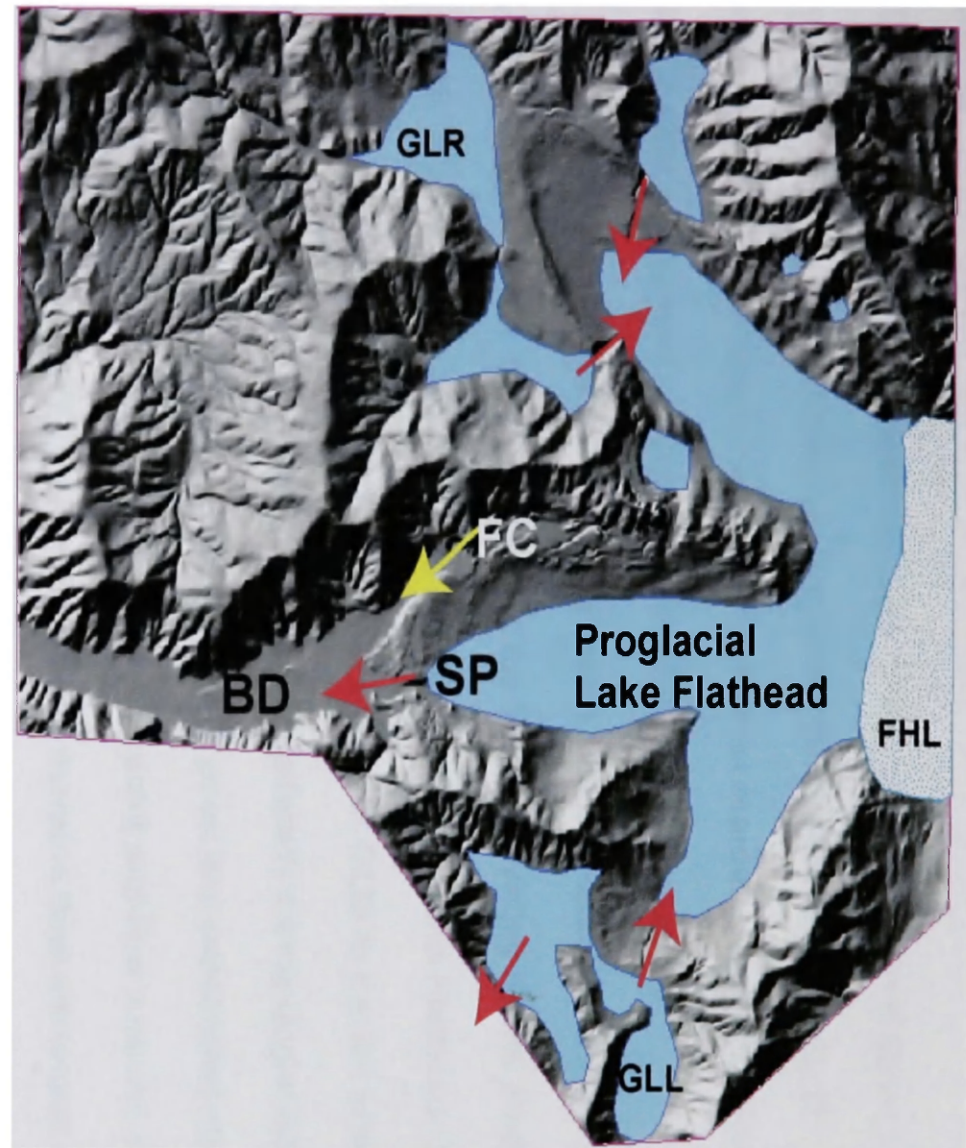


Figure 28. (A) Glaciation of the Big Arm Bay, note the Flathead Lobe (FHL) is partially floating on Glacial Lake Missoula (GLM). (B) The beginning of retreat of the FHL, meltwaters flow along the northern edge of the middle (Elmo) Valley, cutting an ice-marginal stream. Red arrows indicate flow down the stream and out of proglacial lakes.

Figure 29. Final deglaciation of the Big Arm Bay. Proglacial Lake Flathead has down cut the Elmo moraine through the spill point, forming a channel that cross-cuts the ice-marginal stream (yellow arrow) formed during the first stage of deglaciation. Red arrows indicate outwash flows. (BD, Big Draw; SP, Elmo spill point; FC, former channel; GLL, Glacial lake loon; FHL, Flathead Lobe; GLR, Glacial lake mary ronan).



Conclusions

This study combines geologic mapping and sedimentologic analysis of Quaternary deposits in the Flathead Lake in order to interpret the history of glaciation and deglaciation associated with the former margin of the Cordilleran Ice Sheet. Based on my work, I have the following main conclusions:

1. Proctor, Elmo, and Big Arm moraines were formed ~25,000-12,300 ^{14}C year BP due to Pinedale glaciation of the Flathead Valley by the Flathead Lobe. These landforms define the western ice limit of the Flathead Lobe and are helpful for determining the relationship of GLM to the ice sheet.
2. Initial draining of the GLF (proglacial Lake Flathead) during deglaciation of the Flathead Lobe began at the Elmo spill point and proceeded until lake level fell below the elevation of the spill point and flow was cut off. The southern outlet of GLF near the Polson moraine then continued to drain the lake until a lake level of 902 m was established. Ancestral Lake Flathead sediments and shorelines on the Polson moraine confirm this lake level.
3. Relative age relations of geomorphic features in the study area can be inferred based upon cross-cutting relations. For example cross-cutting relations of the outwash channels located in the Elmo Valley suggest two distinct periods of flow prior to and/or during deglaciation of the Big Arm Embayment. The Dayton Creek Delta also provides a relative timeline of deglaciation within the Proctor Valley, suggesting deposition into GLF once the Flathead lobe had retreated.

4. Aquifer and aquitard distribution within Quaternary deposits throughout the three valleys is illustrated by cross-sections that were constructed based on well log data. Glacial lake and morainal sediments are poor aquifers due to poor porosity and silty lithologies. Lenses of gravels and sand within the moraines may have good aquifer quality, but are difficult to locate. The most productive aquifers consist of the outwash (Gm, Sr/Sh) and lake terrace (Sm) facies due the massive sands and gravels present.

Future work

Future work in the area should focus on updating the current knowledge of the depth to bedrock within each of the valleys and the overall structural trends of the Big Arm Bay. More seismic lines should be run at smaller intervals throughout the Big Arm bay and Flathead Lake in order to better understand changes in sedimentary style and the stratigraphy associated with glaciation and deglaciation. The Buffalo Bridge quadrangle and areas located between the Big Arm bay and the Polson moraine should be mapped in detail in order to provide an overview of the whole valley.

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Appendix 1

Clast Count	Elmo Spill Point	Kame Terrace
Green Siltite	5	12
Carbonate with molar tooth structures	13	8
Volcanic clasts	3	2
Red Siltite	2	0
Red Quartzite	9	2
Quartzite	9	4
Green Argillite	2	6
Purple Argillite	11	8
White Quartzite	7	0
Quartzite with rip-up clasts of red argillite	3	1
Brown Siltite	0	6
Pink Quartzite	0	2
total	64	51
average	5.33	4.25

Appendix 2

WAYPOINT ID FOR FIELD STATIONS				
AKB_ID		Latitude	Longitude	elev_ft
	1	N4749.073	W11423.825	3340
	2	N4750.999	W11419.222	3366
	3	N4750.982	W11419.199	3365
	4	N4750.975	W11419.187	3362
	5	N4750.973	W11419.181	3366
	6	N4750.961	W11419.165	3392
	7	N4750.96	W11419.165	3393
	8	N4750.957	W11419.155	3400
	9	N4750.944	W11419.108	3430
	10	N4750.943	W11419.106	3432
ACOL		N4754.03	W11417.049	4024
BA25		N4747.748	W11419.405	3187
BAM1		N4747.282	W11419.009	3164
BAMY2		N4747.09	W11420.443	3649
BANY1		N4747.404	W11419.509	3408
BM1		N4752.515	W11420.878	3704
BM2		N4753.133	W11420.92	3585
DC1		N4755.313	W11420.113	3454
DC2		N4755.917	W11420.07	3622
DCBM		N4755.869	W11419.662	3547
DCWL		N4755.983	W11419.614	3538
E10		N4749.218	W11423.51	3366
E11		N4749.21	W11423.548	3379
E12		N4749.163	W11423.576	3383
E13		N4749.184	W11423.577	3384
E15		N4749.074	W11423.824	3340
E16MP		N4750.146	W11423.123	3335
E20		N4748.545	W11422.603	3469
E21		N4748.598	W11423.041	3531
EDUCK		N4748.851	W11424.844	3509
ELMOYB1		N4748.436	W11421.974	3724
EMD		N4750.545	W11423.011	3481
EMLS		N4749.28	W11424.756	3396
EMNB		N4750.845	W11422.159	3525
PR1		N4754.448	W11420.217	3351
PR6		N4754.553	W11419.705	3329
PRYB		N4753.902	W11418.534	3266
PSG		N4753.306	W11417.275	3102
ROC1		N4753.026	W11419.236	3136